Universitat de Lleida

Formació de la coberta edàfica en diferents àmbits de Catalunya i Llanos de Moxos (Bolívia): casos de predomini d'influència geogènica i antròpica

Jaume Boixadera Llobet

http://hdl.handle.net/10803/385437

Universitat de Lleida

Escola Tècnica Superior d'Enginyeria Agrària

Departament de Medi Ambient i Ciències del Sòl

Tesi Doctoral

Formació de la coberta edàfica en diferents àmbits de Catalunya i *Llanos de Moxos* (Bolívia): Casos de predomini d'influència geogènica i antròpica

Jaume Boixadera Llobet

Director:
Dr. Jaume Porta Casanellas

Lleida, febrer de 2016

Memòria presentada per

Jaume Boixadera Llobet

En satisfacció dels requisits necessaris
per a optar al grau de doctor

Director:
Dr. Jaume Porta Casanellas

Lleida, febrer de 2016

Agraïments

Aquesta tesi és el resultat de molts anys de treball en l'àmbit de l'edafòleg de camp. En aquest llarg període de temps, en que he anat elaborant el material i les idees que després han esdevingut aquesta tesi, són moltes les persones de qui he après, especialment d'aquelles que m'han mostrat aspectes dels sòls que per mi mateix mai hauria vist, o bé que m'han ajudat en les diferents parts d'aquests treballs. La llista seria interminable: professorat, companys i companyes del Departament d'Agricultura, de la Universitat de Lleida, col·legues, pagesos, i tota la gent amb qui l'he compartit, en un moment o altre, en un lloc o altre, els treballs de camp. A tots, el meu agraïment.

No obstant això, he de fer esment d'una manera particular a en Jaume Porta que em va iniciar en l'Edafologia, amb qui he treballat de manera continuada i que ha estat molt més que el Director d'aquesta tesi. També a na Marta López-Acevedo perquè ha tingut un paper rellevant, més del que pugui semblar, a l'hora d'acabar aquesta tesi. També a en Ricard Danés per la seva generositat i a la Carmen Herrero per això, i molt més.

Gràcies, també, a Josep Llop, Montse Antúnez i Rosa M. Poch amb qui he compartit moltes jornades i treballs; no cal dir res més, A Carles Balasch pel concepte sòl-geomorfologia que m'ha permès tirar endavant una part important de la tesi. A Josep Barba i al personal de HOYAM i CEAM pel seu suport a Moxos.

A la Sabina, la Mireia i la Clara.

Al Ramon Lletjos pel seu recolzament i ajuda. A Manel Aragay i a Manel Pérez.

A Carlos Roquero que va ampliar els meus horitzons edàfics i humans. A Emilio Ascaso per la seva ajuda i disponibilitat en tot moment. A Rafa Rodríguez i a Juan Herrero que sempre m'han aportat idees i col·laboració.

A M. Rosa Yagüe perquè sense la seva ajuda mai hagués pogut arribar a veure enquadernada aquesta tesi. El seu recolzament ha anat molt més enllà del que mai podria haver esperat; la seva paciència i cura són impagables.

A l'Àngela i als nostres planςons que m'han acompanyat en aquest recorregut i que han patit les meves absències físiques i anímiques. També a la resta de la família per la seva paciència.

Finalment, i de manera molt especial, vull fer referència als meus primers mestres que varen plantejar altres camins i als meus pares, que els hi feren confiança, a més de proveir-me de tot tipus de suport per assolir la fita.

Resum

El coneixement de com es forma i evoluciona la coberta edàfica és un prerequisit pel seu estudi i per la planificació de l'ús i gestió del territori. Essent el sòl un ens que s'autoorganitza i reacciona davant d'entrades externes, conèixer quines són aquestes entrades i com afecten les propietats i característiques del sòl és també una condició necessària pel seu estudi.

Es ben conegut com el sòl s'organitza a diferents escales i dimensions. Així el podem estudiar des de nivells submicroscòpics, fins a escales regionals o globals. En aquesta tesi s'estudien les cobertes edàfiques a diversos àmbits territorials (principalment de Catalunya, però també dels *Llanos de Moxos* a Bolívia) amb característiques ben diferents. En cadascun d'ells es posa èmfasi en els diversos processos que tenen una importància més gran en el modelat de la coberta edàfica, les escales de temps dels quals varien des d'uns pocs anys a centenars de milers. En tot cas, el seu estudi ha estat sempre amb l'objectiu d'obtenir les claus que permetin explicar l'actual coberta edàfica.

La recerca, que pels seus objectius ha estat de caire pluridisciplinar, s'ha dut a terme utilitzant tècniques que van des de l'estudi del paisatge a la microscòpia. Així, a banda dels reconeixements de camp i de l'estudi de transsectes, s'ha descrit la macromorfologia dels sòls en escandalls, trinxeres, talls i sondatges. A partir de les mostres recollides s'han fet anàlisis de caracterització físico-química, mineralògica i micromorfològica. En un cert nombre de casos s'ha analitzat el pol·len, els fitòlits i s'ha estudiat el carbó vegetal. Finalment, s'han realitzat datacions a partir de tècniques de luminescència o d'anàlisi isotòpica del ^{14}C (carbó vegetal i humus). Aquests treballs es relacionen amb projectes de cartografia o caracterització de sòls en què ha sorgit la necessitat d'aprofundir en la gènesis de la coberta edàfica.

En el primer treball centrat en la part oriental de la Depressió de l'Ebre, la recerca es concentra en els materials parentals de textura llimosa que han donat lloc a un grup important de sòls desenvolupats sobre materials loèssics. Aquest tema havia merescut escassa consideració entre els científics que havien estudiat els sòls i la geologia del Quaternari d'aquesta regió. Malgrat que per alguns autors el loess només té la connotació de sediment eòlic de grandària llim, per d'altres ja comporta en ell mateix un procés edàfic que hom ha anomenat loessificació. La recerca portada a terme posa de relleu que els sòls amb aquest material originari, bé loess o *loess-like*, cobreixen una part significativa de la zona oriental de la depressió del Ebre. Aquests loess, que són molt rics en carbonats i que contindrien una certa quantitat de guix, tindrien el seu origen en àrees del centre de la Depressió de l'Ebre, i s'haurien dipositat en un període entre 17.000 i 30.000 anys en una darrera fase i en més de 130.000 anys en una primera fase.

La recerca duta a terme al Baix Fluvià (Empordà, Girona) posa l'èmfasi en caracteritzar els processos formadors, i en com aquests es lliguen a les geoformes i al temps. Tot plegat té com a finalitat la millora de la comprensió del model sòl-paisatge en què es sustenta la cartografia de sòls, i que ha de servir explícitament per la cartografia de la zona i d'altres properes. A partir de l'estudi de quatre tipus de sòls de referència (*benchmark*), s'aprofundeix en els processos formadors que permeten remarcar la singularitat dels sòls desenvolupats sobre les superfícies Pliocenes de la zona i el caràcter poligènic dels sòls de les terrasses Plistocenes. Es completa amb l'establiment dels trets distintius dels sòls de l'Holocè recent com són el desenvolupament d'estructura en àrees ben drenades (sense arribar a formar horitzons càmbics) i processos de sodificació i alcalinització en antics estanys drenats. Els principals processos formadors (translocació de carbonats, il·luviació d'argila, rubefacció) tenen una expressió diferent segons els materials originaris sobre els que han actuat, els processos geogènics que hi ha hagut (acreció de materials a les superfícies del Plistocè), la finestra de temps en què han actuat determinats processos i també l'acció de humana. La recerca realitzada permet fer també alguna aportació sobre les condicions climàtiques en què s'han desenvolupat aquests sòls.

La recerca desenvolupada als bancals de les Garrigues (Lleida) ha permès datar aquests sòls i, per tant, datar la construcció dels bancals A la vegada, ha permès establir algunes propietats i característiques que podrien ser de diagnòstic per a la seua classificació com a sòl antropogènic, ja que la recerca ho ha mostrat de manera ben clara. També, l'estudi dels pòl·lens, fitòlits i la datació de l'humus enterrat, ha aportat llum sobre aspectes relacionats amb la vegetació, l'ús del sòl i els sòls des de l'època preromana. S'han identificat sòls enterrats que per les seves característiques (estructura, colors foscos) probablement van ser formats en climes més humits que l'actual, i que van formar part del paisatge edàfic fins que van ser coberts per l'abancalament que caracteritza actualment el paisatge de les Garrigues.

Pel que fa a les investigacions realitzades als *Llanos de Moxos*, a Bolívia, una de les planes més grans del món que s'inunden anualment (~100.000 km^2), s'ha vist que els condicionants dels sòls (naturals o lleugerament antropitzats) més destacats són els forts processos d'hidromorfisme i la il·luviació d'argila, però sense que aparegui ferròlisi. Els sòls són moderadament àcids però no hi ha subsòls fortament àcids, ni tampoc la saturació d'alumini supera el 40%. La inundació anual de *los Llanos*, en què els rius provinents dels Andes aporten sediments que inclouen argiles poc meteoritzades (il·lita) a més de cations, explicaria la naturalesa d'aquestes sòls. La recerca sobre els *camellones* (sòls elevats a mode de cavallons) precolombins ha posat de relleu que aquests sòls són, en alguns aspectes, molt similars als del seu entorn (color i contingut de fòsfor, matèria orgànica, absència de carbonats i presencia d' artefactes) però que presenten una variació significativa a escala microtopogràfica (llom i canal del *camelló*) en el pH, la saturació d'alumini, el patró redoximòrfic i la il·luviació (o translocació) d'argila barrejada amb llim. Aquestes propietats i característiques, junt amb d'altres relacionades o externes, com són la morfologia i la informació històrica, haurien de permetre la seua classificació. Alguns dels *camellons* estudiats presenten propietats sòdiques que constitueixen una singularitat. S'ha pogut establir, mitjançant l'estudi de fitòlits que aquests *camellons* van ser usats per al conreu del panís.

Globalment, la recerca que es presenta ha permès aprofundir en el coneixement de la coberta edàfica i en la comprensió de com els processos formadors (amb uns components molt grans geogènics i antropogènics) l'han modelat. Tot això permet millorar el model sòl-paisatge, que és la base de la cartografia de sòls. També s'aporten algunes dades sobre les condicions ambientals en què s`han desenvolupat aquestes cobertes edàfiques, fet que permet un millor coneixement d'altres components del territori. La recerca realitzada té implicacions per a l'elaboració dels mapes de sòls (unitats taxonòmiques i límits de les unitats cartogràfiques) així com dels usos del sòl, però també per a la reconstrucció del passat ambiental de les àrees estudiades.

Resumen

El conocimiento de cómo se forma y evoluciona la cubierta edáfica es un prerrequisito para su estudio y para la planificación del uso y gestión del territorio. Al ser el suelo un ente que se autoorganiza y reacciona ante inputs externos, conocer cuáles son estos inputs y como afectan a las propiedades y características del suelo también es una condición necesaria para su estudio.

Es bien sabido que el suelo, la cubierta edáfica, se organiza en diferentes escalas y dimensiones. De manera que lo podemos estudiar desde niveles submicroscópicos, hasta escalas regionales o incluso globales. En esta tesis se estudian las cubiertas edáficas en diversos territorios (principalmente en Cataluña, pero también en los *Llanos de Moxos* en Bolivia) con características diferentes. En cada uno de ellos se pone énfasis en uno o en diversos procesos, los de mayor importancia en la modelación de la cubierta edáfica. Las escalas de tiempo de los procesos estudiados varían desde unos pocos años a centenares de miles. Su estudio se somete al objetivo de obtener las claves que permitan explicar la actual cubierta edáfica.

La investigación, que por sus objetivos ha sido con un enfoque pluridisciplinar, se ha llevado a cabo utilizando técnicas que van desde el estudio del paisaje a la microscopia. Así, además de los reconocimientos de campo y del estudio de secuencias, se ha descrito la macromorfología de los suelos en calicatas, trincheras, cortes y sondeos. A partir de las muestras recogidas se han realizado análisis de caracterización físico-química, mineralógica y micromorfológica. En un cierto número de casos se ha analizado el polen, los fitolitos y se ha estudiado el carbón vegetal. Finalmente, se han realizado dataciones a partir de técnicas de luminiscencia o de análisis isotópico del C^{14} (carbón vegetal y humus). Estos trabajos se relacionan con proyectos de cartografía o caracterización de suelos en los que ha surgido la necesidad de profundizar en la génesis de la cubierta edáfica.

En el primer trabajo centrado en la parte oriental de la Depresión del Ebro, la investigación se orienta sobre los materiales parentales de textura limosa que han dado lugar a un grupo importante de suelos desarrollados sobre materiales loésicos. Este aspecto había merecido escasa consideración entre los científicos que habían estudiado los suelos y la geología del Cuaternario de esta región. Aunque para algunos autores el loess sólo tiene la connotación de sedimentos eólicos de tamaño limo, para otros ya comporta en sí mismo un proceso edáfico que se ha denominado *loesificación*. La investigación realizada pone de relieve que suelos con este material originario, bien como loess o *loess-like*, cubren una parte significativa de la parte oriental de la depresión del Ebro. Estos loess, que son muy ricos en carbonatos y que contendrían una cierta cantidad de yeso, tendrían su origen en áreas del centro de la Depresión del Ebro, y se habrían depositado en un periodo entre 17.000 a 30.000 años en una última fase y durante más de 130.000 años en una primera fase.

La investigación realizada en el Bajo Fluvià (Ampurdán, Girona) se enfoca hacia la caracterización de los procesos formadores, y en cómo éstos se ligan a las geoformas y al tiempo. Todo ello con la finalidad de mejorar la comprensión del modelo suelo-paisaje en el que se apoya la cartografía de suelos, y que debe de servir explícitamente para la cartografía de la zona y de las áreas próximas. Se parte del estudio de cuatro suelos de referencia (*benchmark*) y, posteriormente, se profundiza en los procesos formadores que permiten remarcar la singularidad de los suelos desarrollados sobre las superficies Pliocenas de la región y el carácter poligénico de los suelos de las terrazas Pleistocénicas. Se completa con el establecimiento de los rasgos distintivos de los suelos del Holoceno reciente como es el desarrollo de estructura en áreas bien drenadas (sin llegar a formar horizontes cámbicos) y los procesos de sodificación y alcalinización en antiguos estanques drenados. Los principales procesos formadores (translocación de carbonatos, iluviación de arcilla, rubefacción) tienen una expresión diferente según los materiales originarios sobre los que han actuado, los procesos geogénicos que se han sucedido (acreción de materiales en las superficies del Pleistoceno), la ventana de tiempo en que han actuado determinados procesos y también la acción del hombre. La

investigación realizada incluye alguna aportación sobre las condiciones climáticas bajo las que se han desarrollado estos suelos.

La investigación desarrollada en los bancales de las Garrigas (Lleida) ha permitido datar estos suelos y, por consiguiente, la construcción de los bancales. A su vez, ha permitido establecer algunas propiedades y características que podrían ser diagnóstico para su clasificación como un suelo antropogénico, ya que la investigación lo ha demostrado fehacientemente. El estudio de los pólenes, fitolitos y la datación del humus enterrado, ha aportado información sobre aspectos relacionados con la vegetación, el uso del suelo y los suelos desde la época pre-romana. Se han identificado suelos enterrados que, por sus características (estructura, colores oscuros), probablemente se originaron en climas más húmedos respecto el actual, i que formaron parte del paisaje edáfico hasta que fueron cubiertos por el abancalamiento que actualmente caracteriza el paisaje de las Garrigas.

En las investigaciones realizadas en los *Llanos de Moxos* (Bolivia), una de las mayores llanuras del mundo que anualmente se inundan (~100.000 km^2), se ha visto que los condicionantes más destacados de los suelos (naturales o ligeramente antropizados) son los fuertes procesos de hidromorfismo y la iluviación de arcilla, pero sin que aparezca ferrólisis. Los suelos son moderadamente ácidos pero no hay subsuelos fuertemente ácidos, ni tampoco la saturación de aluminio supera el 40%. La inundación anual de los *Llanos*, conlleva el aporte de sedimentos por los ríos provenientes de los Andes. Estos sedimentos incluyen arcillas poco meteorizadas (ilita) y cationes, lo que explicaría la naturaleza de estos suelos. La investigación sobre los suelos elevados (*camellones*) precolombinos ha puesto de relieve que estos suelos son, en algunos aspectos, muy similares a los de su entorno (por el color, el contenido en fósforo y en materia orgánica, la ausencia de carbonatos y de otros artefactos) pero que presentan una variación significativa a escala microtopográfica (lomo y canal del *camellón*) en el pH, la saturación de aluminio, el patrón redoxomórfico y la iluviación (o translocación) de arcilla mezclada con limo. Estas propiedades y características, junto con otras relacionadas o externas, como son la morfología y la información histórica, deberían permitir su clasificación. Algunos de los *camellones* estudiados presentan propiedades sódicas que constituyen una singularidad. Se ha podido establecer, mediante el estudio de fitolitos que estos *camellones* fueron usados para el cultivo del maíz.

Globalmente, la investigación que se presenta ha permitido profundizar en el conocimiento de la cubierta edáfica y en la comprensión de cómo los procesos formadores (con importantes componentes geogénicas y antropogénicas) la han modelado. Todo elloo permite mejorar el modelo suelo-paisaje que es la base de la cartografía de suelos. También se aportan algunos datos sobre las condiciones ambientales en que se ha desarrollado estas cubiertas edáficas, lo que permite un mejor conocimiento de otros componentes del territorio. La investigación realizada tiene implicaciones para la elaboración de los mapas de suelos (unidades taxonómicas y límites de las unidades cartográficas) y de los usos del suelo pero también para la reconstrucción del pasado ambiental de la región.

Abstract

The knowledge about the origin of the soil cover and its evolution is a preliminary step in its characterisation but also for land use and land use planning. Self-organization is a soil property. Besides, soil reacts to external inputs. Thus, the knowledge about the main inputs and how they affect soil properties and characteristics is a prerequisite for understanding the soil system.

It is well known that soil is organized at different scales and dimensions. It may be studied from submicroscopic levels up to the regional or even at global scale. In this thesis, several areas with different characteristics are studied, most of them from Catalonia, but also from *Llanos de Moxos* (Bolivia). In each of them emphasis is put on one or several processes having a large role in the shaping of the soil cover. The time scales of the studied processes range from a few years to several hundred thousands. of them. Overall, the aim of the study is to characterize the key processes which can explain the present soil cover.

This research, multidisciplinary due to its objectives, has been done with techniques ranging in scale from landscape analysis to microscopy. In addition to field reconnaissance and traverses, it has described the soil macromorphology in pits, road cuts, trenches and auger cores. The collected samples have been analysed for physicochemical, mineralogical and micromorphological characterization. In some of the samples phytoliths and pollen have been analysed and the charcoal studied. Finally, dating techniques as luminescence and ^{14}C isotopic analysis (charcoal and humus) have been applied. All the work presented in this thesis is related to soil survey projects or soil characterization where the need has arisen for a better understanding of the genesis of the soil cover.

The research of the first paper took place in the eastern part of the Ebro Valley. It deals with the silty parent materials, where a significant number of soils have developed in these loessic materials. The loessic nature of these materials has received little attention from the earth scientists working in the Quaternary in this region. For some authors, loess denotes only silty eolian sediments; for others, the loess means by itself a pedological process called loessification. The developed research highlights the fact that loess or loess-like soils cover a significant hectareage of the eastern Ebro Valley. The loess, very rich in calcium carbonate and with a certain content of gypsum, comes from areas in the centre of the Ebro Valley. The younger deposits were formed between 17000 and 30000 years BP, and the older ones more than 130000 years BP.

The investigation carried out in the Baix Fluvià (Empordà, Girona) emphasizes how the characterization of the soil forming processes is related to landforms and time. The aim is to improve the soil-landscape model supporting the soil survey, able to be used in the area as well in similar ones. Departing from the study of four reference soils (benchmarks), in this project the soil forming processes related to the specific properties and characteristics of the soils developed in the Pliocene surfaces of the region and the polygenetic soils from the Pleistocene terraces was investigated. The overall picture ends with the recent Holocene soils: well-drained calcareous soils (without developing a cambic endopedion) and sodication and alkalinisation in drained former inland lagoons. The main soil forming processes (redistribution of carbonates, clay illuviation, rubification) have different expressions according to the parent material upon which they acted, the geogenic processes taking place (material accretion in the Pleistocene surfaces), the time scale over which some processes have acted and the human action. The research developed also makes some contribution about the climatic conditions under which the soils have developed.

In the study of stone-wall terrace soils (*bancals*) from *Les Garrigues* (Lleida) it has been possible to date these soils and consequently the *bancals*. Also it has been possible to establish some soil

properties and characteristics diagnostic for their classification as an anthropogenic soil and, through the study of pollens, phytollits and humus dating, to gain information about the vegetation, the land use and the soils from Roman times. It has been identified buried soils which by their characteristics (soil structure, dark colour) likely were developed under moister climates than the present ones. They were part of the soilscape until the time where they were covered by the terracing system which is characteristic of the Garrigue's landscape.

In *Llanos de Moxos* (Bolivia), one of the largest areas flooded annually (100.000 km^2) in the world, the main soil (natural or slightly human modified) characteristics include waterlogging and clay illuviation but no ferrolysis. The soils are slightly acidic but without strongly acid subsoils, and the aluminium saturation is not higher than 40%. The annual flood of the Llanos, where the rivers coming from the Andes carry sediments rich in non-weathered clays (illite) and cations could explain the nature of these soils. The research about the Precolumbian fields (*camellones*) shows that these soils are, in certain aspects, very similar to the surrounding ones (colour and phosphorus content, organic matter, non-calcareous, without artefacts), but have a significant difference at microtopographic scale (ridge and channel of the *camellon*), in the pH, aluminium saturation, redoximorphic pattern and clay and silt illuviation from the A_2 horizon. These properties and characteristics, together with other non-soil characteristics such as the land surface morphology or historic information, should allow its classification as a different class. Some of the *camellones* have sodic properties as a singular feature. It has been also possible through the study of phytollites, to establish the cultivation of maize in these raised fields.

The presented investigation allows, globally, increasing the knowledge of the soil cover and the understanding of how it has been shaped by the soil forming processes (with a large geogenic component and anthropogenic parts). All of this allows to improve the soil-landscape model, which is the fundament of the soil mapping. Also some information about the environmental conditions where this soil-cover was developed is given, allowing a better understanding of other land components. Globally, the research carried out has implications for making soil maps (taxonomic units and mapping unit Boundaries) as well as for land use, but also for the paleoenvironmental reconstruction of the studied areas.

ÍNDEX GENERAL

CAPÍTOL 4:

CAPÍTOL 5:

ÍNDEX DE TAULES

ÍNDEX DE FIGURES

CAPÍTOL 1:

Introducció

INTRODUCCIÓ

El sòl constitueix una prima capa on interaccionen l'atmosfera, la litosfera, la hidrosfera i la biosfera i a la que alguns autors anomenen edafosfera, coberta del sòl o edafopaisatge. La coberta del sòl és el continu que consisteix en tots els sòls existents en una àrea determinada. Fruit d'aquestes interaccions abans esmentades en resulta un cos, el sòl, que és un objecte natural composat d'horitzons que canvien lateralment i amb capacitat d'autoorganització (Baize *et al.,* 2013).

El sòls són paisatge però també perfils (Soil Survey Staff, 1951). Les unitats elementals de sòls, els pèdons, s'organitzen en altres unitats superiors que acaben conformant l'edafosfera (Wilding, 1994). Els sòls són també sistemes oberts, que reben i perden matèria i energia a través dels seus límits (Simonson, 1959). Aquests sistemes oberts es caracteritzen per tenir una organització jerarquitzada i poden ser dividits en subsistemes cada cop més petits, els quals són nivells adequats per poder estudiar les diferents qüestions que es plantegen en la recerca edafològica (Dijkerman, 1974). Així, segons autors com Wilding (1994) i Dijkerman (1974), els nivells més alts del sistema són útils per a l'estudi del paisatge edàfic, mentre que els intermitjos ho són per a l'estudi de determinats pèdons representatius d'unitats sòl-paisatge. Altres autors, al referir-se a l'Edafologia, utilitzada en aquest treball amb el mateix significat que en anglès (Pedology) o francès (Pédologie), la consideren com la ciència del desenvolupament del sòl (Sposito i Reginato, 1992), a la vegada que insisteixen en la necessitat d'integrar els resultats de la recerca edafològica amb altres components com l'atmosfera o els oceans. Basher (1997) diu que l'Edafologia és l'estudi dels sòls al camp com a objectes naturals del paisatge. També indica que s'ha de posar més èmfasi en la interpretació de la memòria ambiental que contenen els sòls. Wilding (1994) considera que la Edafologia permet estudiar els diferents subsistemes edàfics d'una forma jerarquitzada i a les més diverses escales de resolució. La metodologia per l'estudi de l'edafosfera es fonamenta conceptualment en la interacció dels factors formadors descrits per Jenny (1941). Aquests factors ja van ser enunciats per Dokuchaev (1898) i han donat lloc al anomenat model sòl-paisatge .

Els mapes de sòls constitueixen una eina bàsica pel coneixement de l'edafosfera i l'estudi del territori. Aquest mapes, qualsevulla que sigui la seva escala, s'elaboren mitjançant l'anomenat paradigma sòl-paisatge que va ser exposat d'una manera molt tardana per Hudson (1992). Aquest autor va formalitzar el que els cartògrafs de sòls ja feien a la pràctica. Els mapes obtinguts mitjançant el que hom anomena cartografia digital de sòls (*digital soil mapping*) es recolzen també, encara que sigui parcialment, en aquest model sòl-paisatge (McBratney *et al.,* 2003; Lagacherie *et al.,* 2006, malgrat que avui es posi èmfasi en nous conceptes i instruments (Vayse i Lagacherie, 2015). Així doncs, la construcció dels mapes de sòls reposa en el model sòl-paisatge que el cartògraf té en el moment d'endegar la realització de la cartografia. El cartògraf anirà millorant el model que té de les relacions sòl-paisatge de l'àrea que està cartografiant a mesura que avança la cartografia. Ara bé, si de bon principi aquest model està ben definit, el mapa serà d'una qualitat molt superior (Western, 1978). El model sòl-paisatge, dins de la classificació de models emprats en Edafologia que fa Dijkerman (1974), és de tipus conceptual i té la funció de ser explicatiu i predictiu alhora. La complexitat d'aquests models fa que en cartografia convencional s'idealitzin mitjançant e.g. toposeqüències, litoseqüències o cronoseqüències. (Dijkerman, 1974). D'altra banda, en la cartografia digital de sòls, el models agafen una expressió matemàtica en un entorn de sistemes d'informació geogràfica.

En els fonaments de la cartografia convencional de sòls s'hi troba la premissa que els efectes dels factors formadors a través dels processos edafogènics han donat lloc a unes propietats i característiques observables dels sòls en un indret determinat. A partir d'aquesta relació s'afirma que es pot predir la presència en el paisatge de sòls amb unes propietats i característiques determinades (Hartung *et al.,* 1991).

Una de les metodologies clàssiques en l'estudi de la coberta edàfica, especialment quan està lligada a la cartografia de sòls, és l'estudi de seqüències diverses (toposeqüències, litoseqüències, cronoseqüències). Les àrees models són de particular interès en cartografia de sòls, tant si s'usen les metodologies convencionals com d'altres de més avançades amb models d'inferència (Lagacherie et al., 1995). De fet, a qualsevol cartografia de sòls, sempre s'acaba aportant informació sobre la distribució lateral i vertical dels cossos edàfics i sobre la seva gènesi. En alguns casos, cal anar més enllà del treball cartogràfic i aprofundir en aspectes puntuals, com ara les característiques de salinitat o en d'altres qüestions més globals com ara la naturalesa dels materials originaris. Molt freqüentment, en conèixer els processos formadors i la seva expressió (macro)morfològica, aquests coneixements es poden utilitzar de manera immediata en la cartografia o inventari de sòls, tant en la fase d'elaboració en camp de la mateixa com en la de correlació de les unitats del mapa de sòls.

La influència del material originari en les propietats i distribució dels sòls va ser reconeguda ja en el mateix moment en què es va desenvolupar el concepte d'Edafologia i va ser inclosa com un dels factors formadors (Jenny, 1941, 1980). La influència dels processos geogènics en els paisatges edàfics ha estat posada en evidència, de manera general, però també amb exemples concrets, per molts autors (Phillips *et al.,* 2005; Hanesch i Scholger*,* 2005). Phillips (2004) alerta dels perills de la distinció artificial que es fa entre geogènic i edafogènic ja que hi ha molts processos superficials que poden ser atribuïts a ambdós.

L'acció humana a través del temps modifica i controla els processos formadors (Bryant i Galbraith, 2002). Aquesta acció existeix arreu i va des d'aquella que té uns efectes gairebé indistingibles fins aquella en què el sòl es presenta profundament modificat. Els processos antropogènics actuen d'una manera molt més ràpida que la majoria dels processos formadors. Les actuacions amb què l'espècie humana modifica els sòls són múltiples, tal i com posa de relleu Sandor *et al.* (2005) en la seva revisió dels impactes de l'home sobre el sòl. Aquests autors hi esmenten els efectes dels abancalaments ancestrals, però no hi inclouen el de les pràctiques antigues de drenatge. Els sòls antropogènics són aquells que ha estat tan afectats pels processos formadors que el canvi de les seves propietats, ja sigui irreversible o reversible, es dona de manera molt lenta (Galbraith *et al.,* 1999). Alguns d'ells han estat classificats com Anthrosols (IUSS, 2014) i es defineixen com aquells sòls en què no és possible reconèixer el sòl original o bé quan aquest ha quedat com a sòl enterrat (Deckers *et al.,* 2002). La majoria han estat poc estudiats dins de l'Edafologia, la qual cosa ha comportat una manca de coneixement important i no ha permès incloure'ls a la taxonomia de sòls i als mapes. La causa d'això és la manca d'una recerca adient que hagi permès identificar els seus trets morfològics i fisico-químics, així com el seu comportament diferencial sobre els sòls (naturals) que els envolten. El poder-los classificar i cartografiar és un aspecte clau per a millorar la qualitat i, per tant, la utilitat i l'interès dels mapes de sòls. Els sòls antropogènics es poden classificar en dues categories en base a si contenen o no artefactes com ceràmica o instruments lítics. Els sòls que no tenen artefactes no poden encabir-se en un únic conjunt de característiques morfològiques que els defineixi (Galbraith *et al.,* 1999).

El ràpid desenvolupament de la cartografia digital de sòls, que ha arribat a la fase operativa a diversos indrets del món (Minasny i McBratney, 2016; Arrouays *et al.,* 2014) té com un input important encara, i segur que per molt de temps, el coneixement de les relacions sòl-paisatge (Minasny i McBratney, 2016; Vayse i Lagacherie, 2015) i amb un model cada cop més formalitzat.

Molt sovint, la necessitat d'aprofundir en la formació del sòl va més enllà de la finalitat cartogràfica, i té per objecte conèixer la història de l'ús d'aquells sòls, o bé com aquells sòls reflecteixen, en les seves propietats i característiques, l'acció antropogènica, la del clima o la dels processos geomorfològics. En la realització de diversos inventaris i cartografies en què ha participat al llarg dels anys l'autor d'aquesta investigació, han aparegut problemes que han fet emergir la necessitat de plantejar una recerca més aprofundida en el coneixement de la gènesi dels sòls estudiats. Aquesta necessitat d'aprofundiment no és únicament en relació amb el model sòl-paisatge sinó que també ho és en relació amb els processos de correlació dels mapes. I ho és tant en els estudis de camp, com en la part final de producció de mapes. També ho és en la correlació regional així com en l'equiparació amb d'altres classificacions i amb els usuaris de la informació (SSS 1951; Ditzler *et al.,* 2003). Per altra banda, Basher (1997) és un dels que ha reclamat que s'interpreti i utilitzi la informació que contenen els sòls com a registre ambiental i com a base del seu ús sostenible.

Hom ha de remarcar que, en molts casos, la recerca que s'ha dut a terme ha estat de caire pluridisciplinari a fi de poder aplicar algunes de les eines de camp i tècniques avançades de laboratori, necessàries per abordar els problemes plantejats. Així mateix, inclou un component important que es correspon amb el que Birkeland (1990) anomena com a estudi sòl-geomòrfic.

Els objectius de la tesi doctoral s'inclouen dins del marc d'aprofundiment en la gènesi dels sòls de diverses àrees de Catalunya i dels *Llanos de Moxos* (Bolívia). Aquests objectius s'articulen al voltant de quatre punts principals:

- conèixer l'origen, la naturalesa, la distribució i les propietats i característiques de certs materials originaris que cobreixen àrees significatives del Sud de Catalunya, així com esbrinar els principals processos formadors que han actuat.

- caracteritzar els processos edafogenètics més importants en quatre sòls de referència a l'Empordà, que s'han desenvolupat en unitats de paisatge representatives. Aquesta caracterització inclou estudis químics, micromorfològics i mineralògics detallats per tal de millorar la comprensió de les relacions sòl-paisatge i així arribar a una millor cartografia dels sòls .

- conèixer els processos formadors de sòls antròpics en dos situacions en què aquests són predominants en el edafopaisatge: els bancals de Les Garrigues (Lleida) i els *camellones* de los Llanos de Moxos (Bolívia).

- contribuir al coneixement de com els sòls estudiats reflecteixen l'acció del clima i de l'home en la seva morfologia i propietats i, per tant, són registres del passat.

La tesi s'estructura en sis capítols. En el capítol introductori es presenta la motivació de la investigació realitzada i els objectius que es volen aconseguir.

En el segon capítol (Boixadera et *al.*, 2015 '*Loess and soils in the eastern Ebro Basin'*) es presenta la recerca duta a terme partint de materials llimosos que s'han trobat en la realització de diverses cartografies en la part sud-oriental de la Depressió de l'Ebre. S'ha demostrat la naturalesa loèssica d'aquests llims, les seves propietats i característiques, s'aporta també la seva distribució i s'apunten possibles àrees font. Es donen dades sobre les èpoques en que es dipositaren i les relacions amb altres events paleoambientals.

En el tercer capítol (Boixadera *et al.*,) s'aprofundeix en els processos formadors que han afectat quatre sòls de referència al Baix Fluvià (Empordà, Girona) per tal de millorar el model sòl-paisatge a la zona. Els principals processos formadors trobats són la translocació de carbonats, la il·luviació d'argila, l'hidromorfisme i la rubefacció. Aquests processos s'expressen de manera diferents segons si hi ha hagut aportacions de nous materials al llarg de la gènesi del sòl, de l'edat de la geoforma i en casos puntuals de l'acció antròpica.

Al capítol 4 (Boixadera *et al*., 2016 '*Buried A horizons in old bench terraces in Les Garrigues (Catalonia)*') l'objecte de la recerca són els bancals de pedra seca de les Garrigues (Lleida). Aquests sòls antropogènics han estat sempre difícils de classificar amb els esquemes i informació existent fins ara. S'han pogut definir un conjunt de propietats dels sòls dels bancals que podrien ser emprades per la seva classificació. També s'han pogut datar per a conèixer el paisatge vegetal en l'època en que es van construir i l'ús posterior.

Al capítol 5 (Boixadera et *al*.,) la recerca es centra en els sòls dels camps elevats precolombins (c*amellones*) dels *Llanos de Moxos* a l'Amazònia boliviana. S'ha vist que els sòls dels *camellones* són sòls antropogènics que en algunes propietats no difereixen dels sòls de l'entorn (color, artefactes, carbó, fòsfor) però presenten diferències significatives a nivell de trets redoximòrfics: pH i saturació d'alumini. Aquests trets es podrien utilitzar com a criteris de classificació. També ha estat possible establir l'ús pel cultiu del blat de moro en època precolombina mitjançant l'estudi dels fitòlits.

En el darrer capítol es fa una discussió general dels principals resultats de la recerca desenvolupada en relació a la coberta edàfica, als factors geogènics i antropogènics, als processos formadors que han afectat aquests sòls i a la seva classificació. Abans de les conclusions es discuteixen també com aquests resultats permeten interpretar l'historia paleoambiental d'aquests sòls i de l'entorn on es troben.

Referències

Arrouays D, Grundy MG, Hartemink AE, Hempel JW, Hong SY, Lagacherie P, Lelyk G, McBratney AB, McKenzie NJ, Mendonca-Santos MD, Minasny B, Montanarella L, Odeh IOA, Sanchez PA, Thomposon JA, Zhang GL. 2014 GobalSoilMap, Toward a fine-resolution global grid of soil properties. *Advances in Agronomy* **125**: 93-134.

Basher LR. 1997. Is pedology dead and buried?. *Australian Journal of Soil Research* **35**: 979-994.

Birkeland PW. 1990. Soil-geomorphic research-a selective overview. *Geomorphology* **3**:207-224.

Baize D, Duval O, Richard G. 2013. Les sols et leurs structures. Observations à différentes échelles. Éditions Quae. Collection Synthèses, pp. 265.

Boixadera JB, Poch RM, Lowick SE, Balasch JC. 2015. Loess and soils in the eastern Ebro basin. *Quaternary International* **376**: 114-133.

Boixadera JB, Riera S, Vila S, Esteban I, Abert RM, Llop JM, Poch RM. 2016. Buried A horizons in old bech terraces in Les Garrigues (Catalonia). *Catena* **137**: 635-650.

Bryant RB, Galbraith JM. 2002. Incorporating anthropogenic processes in soil classification. Soil classification: A global desk reference. CRC Press, Boca Raton, FL, pp. 57-66.

Deckers JA, Driessen PM, Nachtergaele FO, Spaargaren OC. 2002. World reference base for soil resources. *In*: Encyclopedia of Soil Science, pp. 1446-1451. Marcel Dekker.

Dijkerman JC. 1974. Pedology as a science: The role of data, models and theories in the study of natural soil systems. *Geoderma* **11**: 73-93.

Ditzler CA, Engel RJ, Ahrens RJ. 2003. Soil taxonomy and soil survey, pp. 221-230. Eswaran H, Rice T, Ahrens R, Stewart BA. (Eds.). CRC Press: Boca Raton, FL, USA.

Dokuchaev VV. 1898. Writings, vol. 6. Akad. Nauk, USSR, 381.

Galbraith JM, Bryant RB, Russell-Anelli JM. 1999. Major kinds of humanly altered soils. Classification, Correlation, and Management of Anthropogenic Soils, Proceedings Nevada and California, September 21e October, 2(1998), 115-119.

Hanesch M, Scholger R. 2005. The influence of soil type on the magnetic susceptibility measured throughout soil profiles. *Geophysical Journal International* **161**: 50–56.

Hartung SL, Scheinort SA, Ahiens RJ. 1991. Scientific Methodology of the National Cooperative Soil Survey. 39-48. Mausbach, M.J. Wilding, L.P. Spatial Variabilities of Soils and landforms SSSA Sp. Publ 28.

Hudson BD. 1992. The soil survey as paradigm-based science. *Soil Science Society of America Journal* **56**: 836-841.

IUSS Working Group WRB, 2014. World reference base for soil resources. *In*: World soil resources reports No. 103 FAO, Rome.

Jenny H. 1941. Factors of soil formation: a system of quantitative pedology. McGraw-Hill. New York.

Jenny H. 1980.The soil resource. Origin and behaviour. *Ecological studies* **37**. Springer-Verlag. New York. Inc.

Lagacherie P, Legros JP, Burfough PA. 1995. A soil survey procedure using the knowledge of soil pattern established on a previously mapped reference area. Geoderma **65**: 283-301.

Lagacherie P, McBratney A, Voltz M. 2006. Digital soil mapping: An introductory perspective. Developments in soil science. Vol. 31, pp. 658. Elsevier.

McBratney AB, Santos MM, Minasny B. 2003. On digital soil mapping. *Geoderma* **117**(1): 3-52.

Minasny B, McBratney AB. 2016. Digital soil mapping: A brief history and some lessons. *Geoderma* **264**:301-311.

Phillips JD, Luckow K, Marion DA, Adams KR. 2005. Rock fragment distributions and regolith evolution in the Ouachita mountains, Arkansas, USA *Earth Surface Processes Landforms* **30**: 429–442.

Phillips JD. 2004. Geogenesis, pedogenesis, and multiple causality in the formation of texture-contrast soils. *Catena* **58**: 275–295.

Sandor J, Burras CL, Thompson M. 2005. Human impact on soil formation, pp. 520-532. *In:* Hillel (Ed.) Encyclopedia of soils in the environment, Vol 1. Elsevier Ltd., Oxford, U.K.

Simonson RW. 1959. Outline of a generalized theory of soil genesis. *Soil Science Society of America Journal* **23**: 152-156.

Soil Survey Staff. 1951. Soil survey manual. U.S. Deparment of Agriculture Handbook Number 18. U.S: Department of agriculture, Washington, D.C.

Sposito G, Reginato RJ. 1992. Pedology: The science of soil development. *In*: Sposito G, Reginato RJ (Eds.). Opportunities in basic soil science research. Soil Science Society of America, 9-25, Madison, Wisconsin.

Vaysse K, Lagacherie P. 2015. Evaluating digital soil mapping approaches for mapping global soil map soil properties from legacy data in Languedoc-Roussillon (France). *Geoderma Regional* **4**: 20-30.

Western S. 1978. Soil survey contracts and quality control. Oxford University Press. Oxford.

Wilding LP. 1994. Factors of soil formation: contributions to pedology. *In*: Amundson R, Handen J, Singer J (Eds.). Factors of soil formation: a fiftieth anniversary retrospective. *Soil Science Society of America. Special Publ*., **33**: 5-30.

CAPÍTOL 2:

Loess and soils in the eastern

Ebro Basin

Article published:

Boixadera, J., Poch, R.M., Lowick, S., Balasch, J.C. 2015. Loess and soils in the eastern Ebro Basin*. Quaternary International* 376: 114-133. *DOI: 10.1016/j.quaint.2014.07.46.*

LOESS AND SOILS IN THE EASTERN EBRO BASIN

Jaume Boixadera[1,2], Rosa M. Poch[2*], Sally Lowick[3] and Carles Balasch[2]
[1]Departament d'Agricultura, Ramaderia, Pesca, Alimentació i Medi Natural, Generalitat de Catalunya.
[2]Departament de Medi Ambient i Ciències del Sòl, Universitat de Lleida, Lleida (Catalonia).
[3]Institute of Geological Sciences, University of Bern, Switzerland.
[*]corresponding author rosa.poch@macs.udl.cat

Abstract

Wind-blown sandy and silty deposits were formed during the late Quaternary at the NE of the Iberian Peninsula. They are the most significant in the West Mediterranean region, together with those described in the Tagus River basin (Iberian South Subplateau), forming small scattered patches across parts of the SE Ebro Depression and SW Catalan Mediterranean Range. Two major depositional environments are distinguished. The first (largest) outcrop covers the lower Ebro reaches on the SE border of the Ebro Depression, the Prelitoral Coastal Range and the Móra d'Ebre Basin. A second outcrop, to the north, consists of a few patches scattered over a wide amphitheatre surrounding the western tributaries of the Segre River, from the wind-exposed Segrià platforms to the Almenara Range in its northernmost part. They consist of highly sorted fine sands and silts, 1 to 12 m thick (though most typically 3 - 4 m thick), and coarser than typical loess. They are highly uniform, lack any sedimentary structures and are pale ochre in colour. The deposits are calcareous (30-45% $CaCO_3$), basic to alkaline and with some soluble salts.

Five selected sequences of primary loess (namely Mas de l'Alerany,Tivissa, Guiamets, Batea and Almenara) were studied to ascertain deposit characteristics and soil development. All sections show a consistent vertical granulometric variability that may be attributed to wind intensity changes, and hinders the recognition of spatial particle size distribution. Pedogenesis is mostly related to calcium carbonate redistribution, which accumulates as nodules, large rhizocretions or biogenic calcite. Secondary gypsum (Batea and Almenara sequences) is probably related to primary gypsum blown from the source areas that was redistributed by leaching and precipitation at the bottom of the profiles. In a few places (Mas de l'Alerany outcrop) a fersialitic, rubefacted-recalcified soil indicates the presence of an older generation of loess. While the dominant WNW winds and particle coarseness suggest that the loess originates from nearby alluvial fans and fluvial plains, the presence of gypsum and Mg anomalies may be evidence of more distant sources of the Central Ebro Depression and Ondara-Corb alluvial fans.

Optical Stimulated Luminiscence (OSL) ages for the more recent deposits (Guiamets, Batea, Almenara) are between 18 and 34 ky, while the old Mas de l'Alerany sequence is more than 115 ky old. These ages indicate loess deposition during the last cold phases of the Quaternary and with pedogenesis occuring during warm interglacial periods.

Keywords: Loess, Ebro Valley, Last Glacial Maximum, pedogenic gypsum, pedogenic carbonates.

2.1. Introduction and objectives

The term loess (from the German löss) was first applied by von Leonhard in 1823 to describe friable silty deposits found in the Rhine valley and was then promoted by Lyell (1834-1846) during a visit to the Mississippi loess valley. Despite its early description, the aeolian origin of these materials was not accepted until the late nineteenth century, when the huge extent of these deposits was recognised in many parts of the world, i.e. Central Europe, Russia and China. It is now estimated that about 10 % of the Earth's surface is covered by loess (Pye, 1995).

From the early twentieth century a distinction was made between primary eolian and secondary loess (loess-like), which results from the removal and redeposition of primary loess. Towards the middle of the last century, the need for weathering and pedogenic processes to acquire the typical characteristics of loess deposits, as opposed to simple windblown dust was postulated, requiring a certain time for accumulation (Pecsi, 1990).

Smalley and Vita-Finzi (1968) described loess as clastic deposits, predominantly quartz of 20-50 µm diameter (mode of 30 µm), that were transported and deposited by wind. However, loess displays a greater complexity and a larger variation in characteristics, such as thickness of the deposits, particle size (varying modal intervals from 8-16 µm in the China Plateau, to 50-65 µm in Nebraska (USA)), colour, mineralogy, geochemical composition, geotechnical characteristics and morphology. Although the origin of the silt was initially attributed to areas with glacial sediments (glacial loess), it was later acknowledged that in some regions the dust was sourced from desert areas (Yaalon and Ganor, 1973), and was therefore referred to as peri-desertic loess (Smalley and Vita-Finzi, 1968; Yaalon, 1987). Some authors (Wrigth, 2001) have stressed the significance of environmental, tectonic and geomorphological factors at all stages in the formation of loess sequences, as opposed to focussing only on their origin. Other authors (Iriondo and Kröhling, 2007) refer to other geomorphic processes, parent materials (as pyroclastic or gypsum rocks) and environments involved in the generation of loess, in order to emphasize the complexity of formation processes and sources.

Pecsi (1990) listed the characteristics required for a deposit to be considered typically loessic, although not all described loess meets each of these characteristics (Pye, 1995).The vast majority of loess deposits display evidence of some degree of modification or reworking with post-depositional bioturbation, weathering and pedogenesis, but these changes are not considered essential for qualification as a loess deposit.

Mediterranean loess deposits were only recognised late in the twentieth century (Brunnacker, 1969; Yaalon, 1969; Bornand et al., 1977; Brunnacker, 1980; Coudé-Gaussen *et al.,* 1982, 1983; Cremaschi *et al.,* 1990). The preparatory work for the 1957 INQUA excursion involved an update on the knowledge and extent of loess in Spain, although some participants had already ackowledged their presence (eg. Solé Sabarís *et al.,* 1957). At that time, silty deposits of aeolian origin had already been recognised in the Manresa area of Catalonia (IGME, 1956). Since then, Spanish authors have overlooked the presence of such deposits and only foreign authors have mentioned them: in Andalusia (Brunnacker and Lozek, 1969; Günster *et al*., 2001), and the Levant region (Dumas, 1977). However, extensive accumulations of loess in the Middle of the River Tagus Valley (García-Giménez and González, 2010; García-Giménez *et al*., 2012) and the Castilian branch of the Iberian and South Submeseta (González *et al*., 2000) have recently been reported. Some small areas have been dated to the Middle Pleistocene, although the most extensive areas date from the Upper Pleistocene with an age of 42.7 ky BP, and a group of small areas date from the Pleistocene-Holocene (11.1-12.1 ky BP) (García-Giménez and González, 2010).

With respect to the Ebro basin, several authors (Torras and Riba, 1968; Fink, 1969; Faraco, 1975; Mensúa and Ibáñez, 1975; van Zuidam, 1976; Gutiérrez-Elorza *et al*., 2002; Iriondo and Kröhling, 2004) referred to “gypsum silts”, giving them an aeolian origin in some cases. In the lower Ebro Valley geologists have recognized for a long time the presence of silty deposits, while carefully avoiding the use of the term loess (IGME, 1981). In spite of this, several authors have reported soils developed on loess in NE Spain (Bech and Solé, 1977; Maldonado *et al*., 1979; Gallart, 1981; Josa, 1985; Solé-Benet *et al*., 1988; Mücher *et al*., 1990; Lewis *et al*., 2009), although little relevant information regarding its origin and characteristics has been provided. Courty and Vallverdú (2001) mention aeolian deposits with a typical loess size in Abric Romaní (Capellades).

Our research has been conducted in an area NE of the Iberian Peninsula, east of the Segre River and south of the Sió River (Fig. 2.1) and lower Ebro Valley, up to the Benifallet canyon. For simplicty we call this area the Eastern Ebro valley. While the existence of other loess or loess-like deposits east of this canyon are known (DAR, 2010; Maldonado *et al.*, 1979), our study is restricted to this area where more information was available.

The soils of NE Iberian Peninsula have been surveyed since 1984 at the 1:25.000 scale (Danés *et al*., 1991). During the surveys, soils on widespread sandy loam materials were identified in the lower Ebro Valley (DARP, 1987; Boixadera *et al.,* 1989); they did not fit the existing descriptions of Quaternary deposits of the area, and could not be explained by fluvial, alluvial, colluvial or gravitational processes. The properties (grain size, sorting, colour, micromorphology, geotechnical behaviour) and the geomorphological outcropping of these deposits corresponded to loess or loess-like materials (Balasch *et al*., 2010; 2011).

The aim of this research is to present the extent, characteristics and significance of these deposits in the SE Ebro Depression and SW Catalan Coastal Range, to determine their loessic nature, to describe the extent of pedogenesis on them, and to propose source areas and ages for the aeolian material. This information contributes to the understanding of the paleoenvironmental and climatic conditions of the NE part of the Iberian Peninsula during the Quaternary and the role of loess in the present day soil cover.

2.2. The physical setting

The Ebro Basin is a Tertiary sedimentary basin that developed and filled during the Paleogene and early Neogene, after which it was drained and carved by the Ebro River (Fig. 1a). It is bounded to the north by the Pyrenees, by the Iberian southwest ridge, and to the southeast by the Catalan Coastal Range. The Pyrenees reach almost 3,500 m, are composed mainly of granitic and metamorphic rocks, that were largely covered by ice during diferent phases of the Quaternary. The last presence of ice in the Pyrenees valleys was about 15,000 years ago (Calvet *et al*., 2011), with only cirque glaciers present during the Little Ice Age.

The oldest Paleogene sediments in the Ebro Depression outcrop in its eastern and northern margins, consisting of marine detritic and carbonate rocks. After a regression, most of the sedimentary fill of the basin was formed of continental detritic sequences (conglomerates, sandstones and lutites) as well as evaporitic rocks. The center of the Ebro Basin is covered by outcrops of lutites, sandstones, limestones and gypsum, as well as Quaternary unconsolidated deposits associated to the drainage system (terraces and aluvial fans) and lacustrine deposits in endorheic playa-lake areas (e.g. Las Saladas de Monegros). The origin of the extensive Quaternary powdery gypsum surface deposits in this semi-arid region is not due to wind or desert processes, but was identified as the result of a soil forming process (Herrero 1991; Herrero *et al*., 1992; Artieda, 2013). Some of the lutites of the easthern Ebro Depression fringe also contain diagenetic fibrous gypsum.

Other Quaternary detrital deposits include those covering the Pla d' Urgell east of Lleida; alluvial fans of the Corb and Ondara Rivers flowing from east to west, that spread over the plain, with no connection with the Segre River (Fig. 2.1b). Soils with high amounts of gypsum have been described on these Quaternary calcareous materials (Poch, 1992, Herrero *et al*., 1993). The Serra d'Almenara, extending W-E, is located North of these alluvial fans, and can be considered the southernmost folded structure of the pre-Pyrenean ranges, caused by the Alpine orogeny.

Before arriving at the Mediterranean sea, the Ebro River (Lower Ebro Valley) crosses the SW section of the Prelitoral Coastal Range (Catalan Coastal Range), also due to Alpine folding. There, the geomorphological unit of the Móra basin, within the Prelitoral system is found (Fig, 1b). To the east, the Móra basin limits are composed of Paleozoic and Mesozoic materials; to the northwest, it is separated from the Ebro Basin by the Pàndols-Cavalls unit linking with the Ports of Beseit and Montsant ranges, and closing the depression.

The present climate of the central Ebro valley is hot and very dry, and with an area of ~ 12,000 km^2 that receives only 300-400 mm of rainfall per year. This area is characterized by high insolation and evapotranspiration of between 1000-1500 mm/yr. The local wind is the *cierzo* blowing predominantly from the WNW (more than 100 km/h or 28 m/s 8 days per year) through the corridor of the Ebro Valley, and caused by a pressure gradient formed between an Atlantic high (Açores) and a Mediterranean low. Average wind speeds are 4.5 m/s at 10 m height, 5.5 m/s at 30 m height and 6 m/s at 50 m height, although 40% of the time the gusts have an average speed higher than 8 m/s. The maximum gusts measured at the Zaragoza station reached 44 m/s in 1954 and 38 m/s in 1979 (López-Martín *et al*., 2007). The available literature suggests that the general atmospheric circulation over this area of the Iberian Peninsula has remained the same during the Quaternary, with the wind regime prevailing from WNW (Mensua and Ibáñez, 1975).

At present, the Ebro basin land uses are dominated by agricultural activity,although some remnants of open woodland of *Pinus halenpensis*, *Quercus* and *Juniperus* still exist, together with dense shrublands. Although the vegetation of the Ebro Basin and its evolution during the Glacial and Lateglacial is debated, pollen records suggest for its central part, a steppe vegetation during the cold and arid episodes accompanied by Mediterranean shrubs, coniferous forest and mesothermophilous taxa (González-Sampériz *et al*., 2005).

2.3. Material and methods

2.3.1. Areal extent and distribution of loess deposits

Information from previous soil surveys (Margarit and Monner, 1996; Boixadera and Rosell, 1997; Carrillo *et al*., 1997; DAR, 2010), from non cartographic soil reports (Abellà, 2011) and from transects and other field work were used to determine the extent of the loess deposits.

The identified loessic deposits cover an area of aproximately 425 km^2, forming a patchy, thin, discountinous cover scattered on a 1000 km^2 depositional surface. Most deposits have typical loessic characteristics, but many others exhibit those properties referred to as loess-like. The thickness of the the most prominent deposits is between 3 to 4 m, although they may reach 12 meters in thickness. Thicknesses below 1m are rarely identified due to erosion and high agricultural activity. They cover a diversity of landforms, such as structural platforms, slopes, valleys, Ebro terraces and glacis.

The occurrence and thickness of the loess deposits appear to be related to the presence of transverse orographic obstacles acting as traps in the course of the prevailing regional W and NW winds. In relation to this, it is possible to distinguish two main depositional areas depending on their situation, proximity and relationship with these geographical structures (Fig 2.1b):

The area with the largest outcrops (340 km^2) is related to the lower reaches of the Ebro River SE part of the Ebro Depression, the Prelitoral Coastal Range and the Móra d'Ebre basin subunits. The first trap is related to the relief of the Pàndols and Cavalls ranges which force the capture of eolian sediments on depressed footslope areas. A second trap for the eolian silts and sands are the corridors and valley bottoms of the Ebro River itself. This is the case with the accumulations trapped by the confluence of the Segre (Ebro tributary) with the Pas de l'Ase, where the Ebro crosses the Prelitoral Coastal Range. The Pas de l'Ase canyon is 100 km long, and is the lowest point of the alignment of the ranges, acting as a barrier from the Ports de Beseit to the Monsant. In this first area four depositional units of eolian sediments are recognized:

1. *Batea-riu Sec*. This is the westernmost unit. It forms a crescent from Casserres village and the headwaters of the Algars River (leeward), through Corbera, Gandesa, Coll de Camposines, to the Sec River valley, where it forms a belt at the footslopes of the Pàndols and Cavalls ranges. The thickness of the deposits in the windward valleys (Batea) can reach 7 m, but generally have thicknesses of 2-4 m.

2. *Móra d'Ebre basin*. In this basin, loess deposits cover different geomorphological positions at altitudes ranging from 20 to 300 m a.s.l. They have variable thicknesses, generally 3-5 m but they increase on windward slopes -the footslopes of the Llaberia and Tivissa mountains- where the sequences can reach 12 m thickness. The best preserved and most complete loessic outcrops are found in this unit (Mas de l'Alerany).

3. *Ebro valley from Riba-Roja to the Pas de l'Ase canyon*. This consists of extensive deposits, mainly loess-like, from Riba-roja, Flix, and Ascó to Vinebre. East of Ebro River, in the Riba-roja – Vinebre area, the accumulations are up to 4 m thick, and thin as they move away to the east (Bovera, Palma d'Ebre).

4. *Ebro valley from Segre River confluence to Algars River confluence*. This set of deposits includes the primary loess, on the Segrià platform between Montmaneu and Almatret, about 1 m thick, and the redistributed loess-like deposits at Mequinensa and Faió on the lowest parts of the slopes down to the Ebro River, where they can reach thicknesses of 5-6 m (Mequinensa).

A second area, E of the Ebro Depression, contains very few outcrops (85 km^2), scattered over a wide amphitheater relief surrounding tributaries to the left of the Segre River from the Set to the Sió Rivers. The deposits are rather discontinuous, dispersed, and thinner than the previous ones. They can be subdivided into 3 subareas:

5. *Cogul*. This includes the outcrops from Alcanó and Cogul to La Granadella, on wind-exposed platforms at the southern side of the Set River, 1-2 m thick.

6. *Borges*. This is the smallest unit on the headwaters of the Femosa River. It extends between Les Borges Blanques and La Floresta, with deposits 1 m thick.

7. *Almenara.* This is the northernmost unit. These 1-3 m thick outcrops are very dispersed, found on back cuesta landforms, on the north flank of Barbastro-Balaguer gypsum anticline and to the south of the Sió River. The Ondara and Corb Rivers have formed vast alluvial fans at the bottom of this structure.

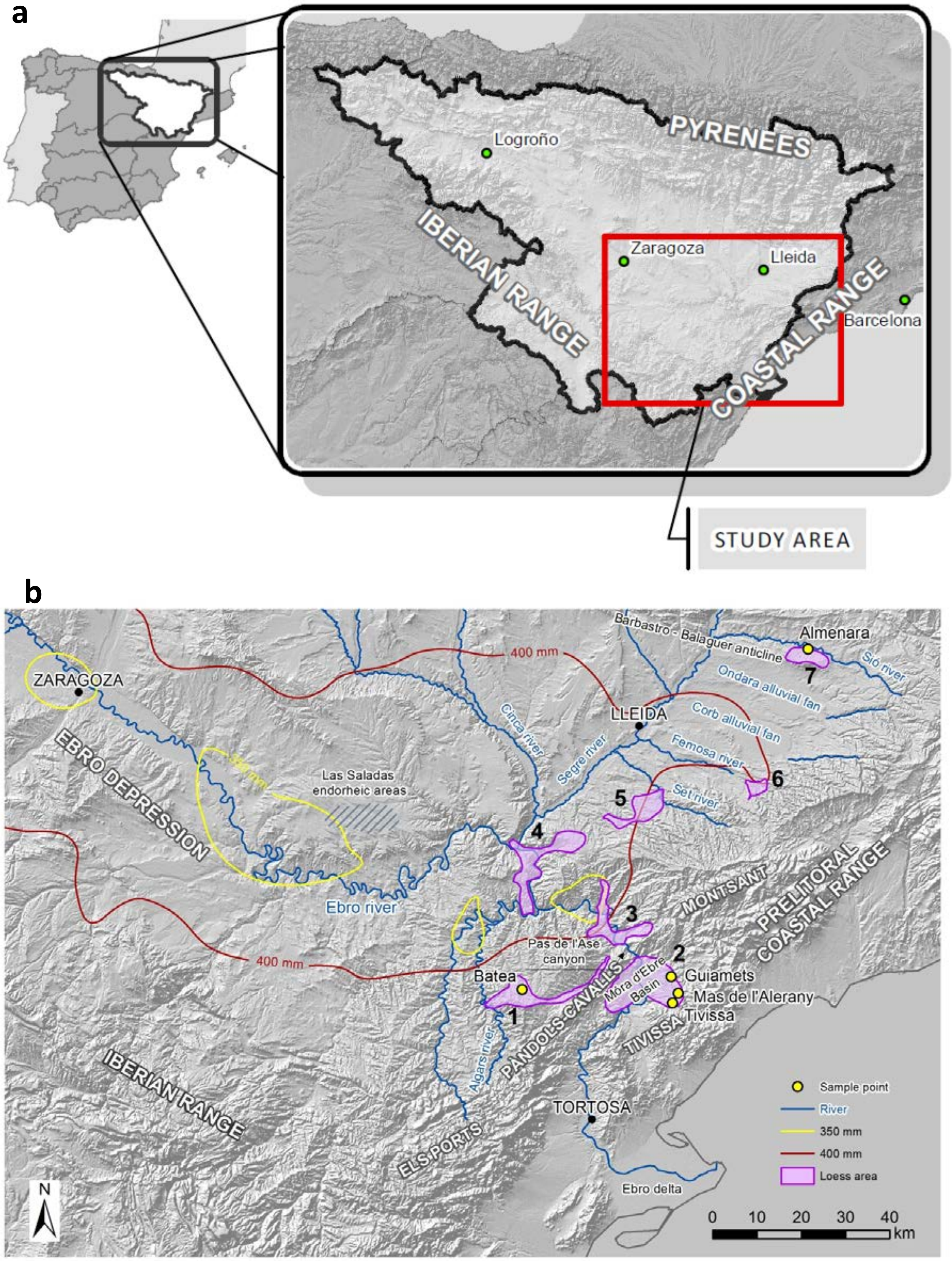

Figure 2.1. Main areas of loess deposition in the study area. Numbers refer to the areas described in the text. Circles indicate the sequences selected for further study

2.3.2.The sequences selected for study

In order to ascertain the main characteristics of the loess and the soil development on them, and following earlier extensive surveying and sampling (Balasch *et al*., 2011; Abellà 2011), five of the best developed and preserved sequences, namely Guiamets, Tivissa, Mas de l'Alerany, Batea and Almenara (Table 2.1, Figs. 2.1, 2.2, and 2.3) were selected, described and sampled for chemical, physical, micromorphological, submicroscopical and dating analyses. The geomorphic units where these sites are located are as follows:

- Guiamets: Mountain top, isolated platform on alluvial Oligocene deposits. Primary loess.

- Tivissa: Corner of a platform on Jurassic limestones. Primary loess, windward.

- Mas de l'Alerany: Corner of a platform on alluvial Oligocene deposits. Primary loess, windward.

- Batea: Slope on Oligocene deposits with secondary gypsum. Primary loess in the upper part, windward.

- Almenara: Very gentle slope, leeward.

All these sequences show unmistakable features typical of primary loess, located in upper positions of the landscape and lack fluvial/colluvial structures within primary sequences, as Crouvi *et al*. (2009) note.

The soils developed on these loess deposits were mostly classified as Calcisols (IUSS Working Group WRB, 2006).

Table 2.1. Location of the selected loess sequences

	Coordinates*	Altitude (m asl)	Position	Thickness	Underlying material
Batea	X 275805 Y 4550107	393	Middle and lower section of a slope, windward.	3 m (top) 10 m (bottom)	Oligocene sandstones and lutites.
Tivissa	X 309481 Y 4547083	281	Upper section of a slope, at the bottom of the Tivissa range. Windward.	2.5 m (top) 9 m (bottom)	Jurassic limestones.
Mas de l'Alerany	X 310701 Y 4549386	248	Upper section of a slope and flat platform, windward.	9 m	Oligocene sandstones and lutites.
Guiamets	X 309093 Y 4553113	179	Upper section of a bench-terraced slope, windward.	4 m	Oligocene gravels and boulders. Petrocalcic horizon at the top of the sequence.
Almenara	X 339673 Y 4626930	349	Northern flank of an anticline, slightly tilted. Leeward.	3 m	Oligocene lutites, limestones and sandstones.

*reference system ETRS89 UTM31 zoneT

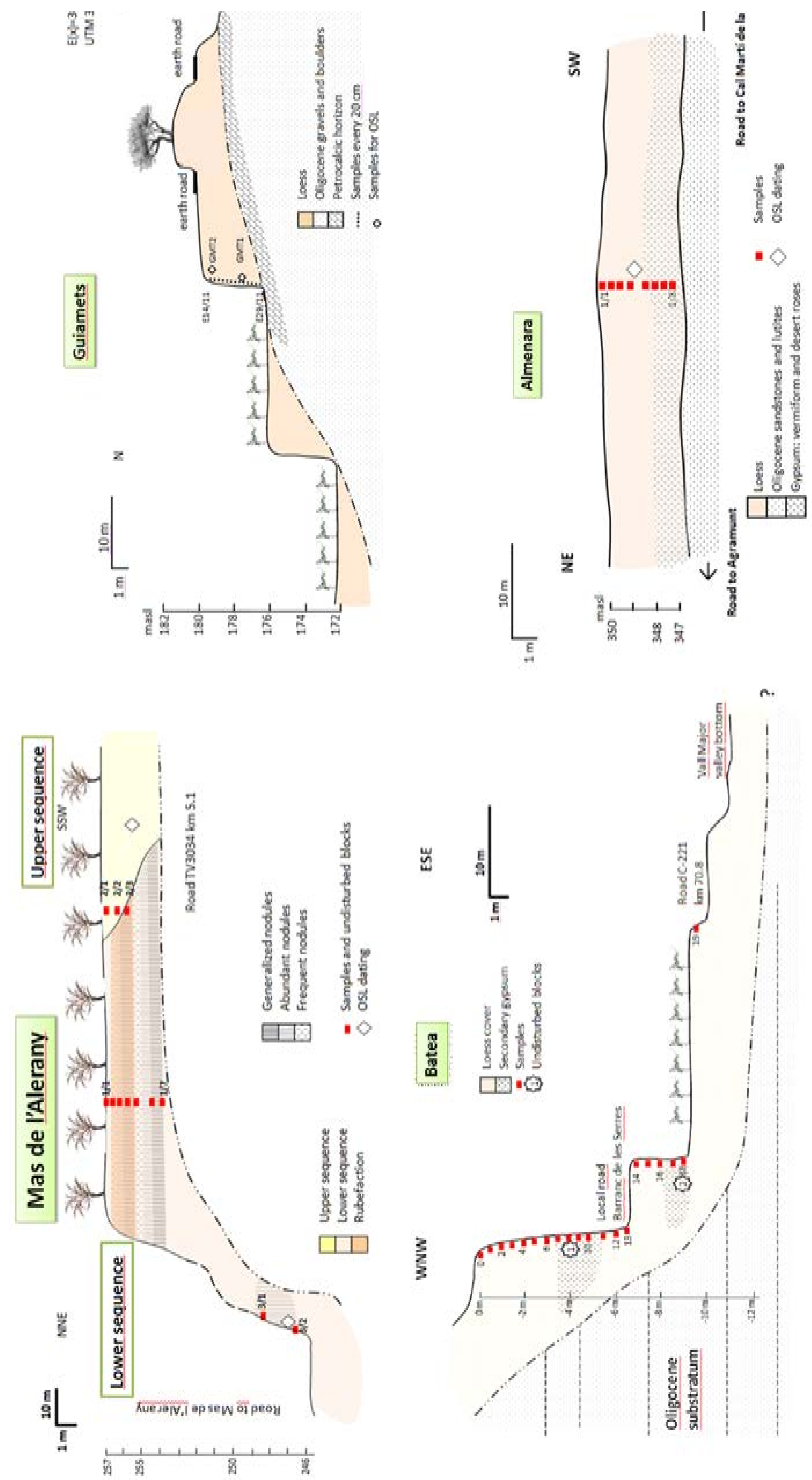

Figure 2.2. Schemes of the locations of the samplings: Mas de l'Alerany, Batea, Almenara and Guiamets

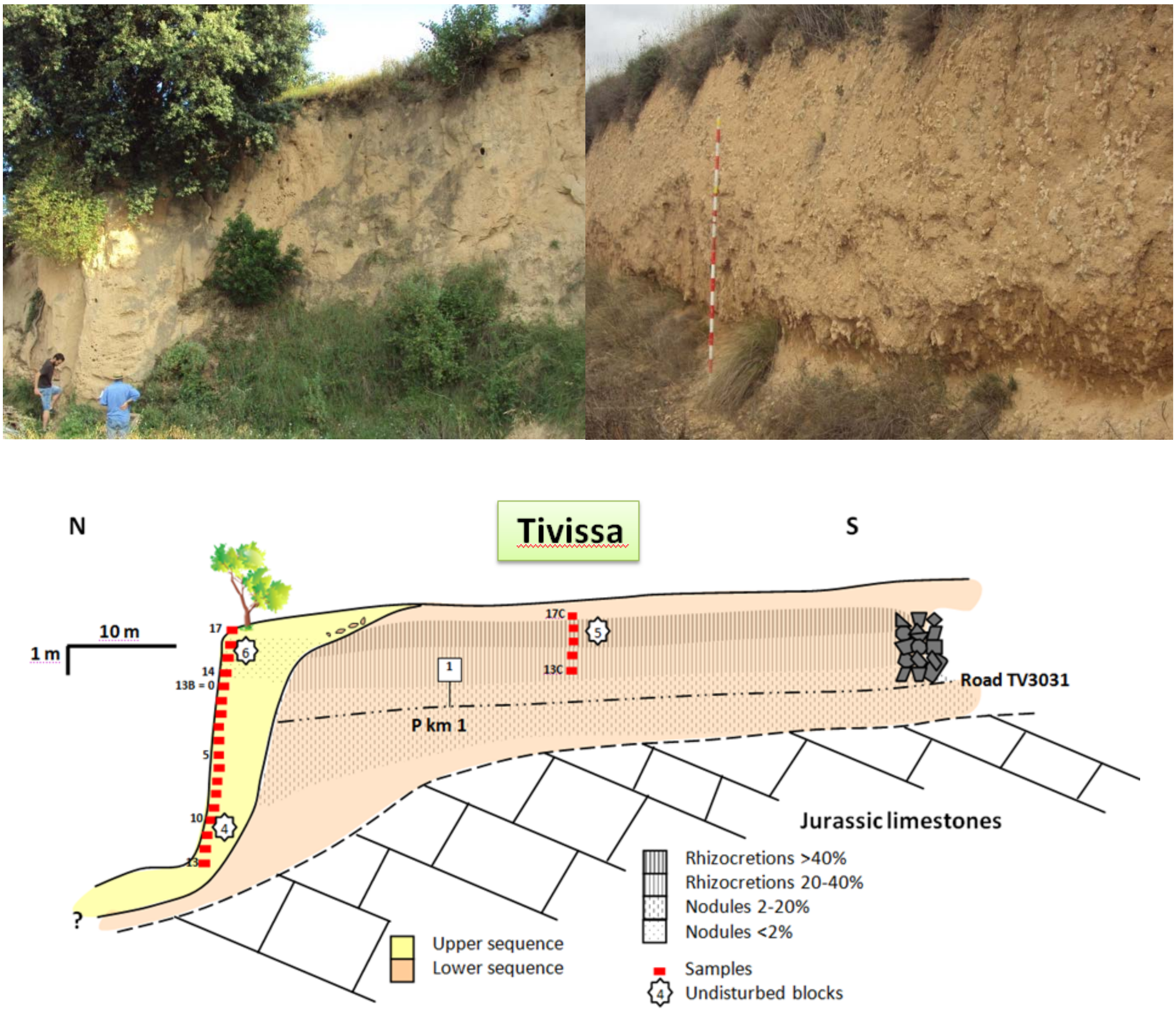

Figure 2.3. Tivissa lower (left) and upper(right) sequences and scheme of the outcrop. Note the prominent calcareous rhizocretions in Tivissa upper

2.3.3. Description and physico-chemical analyses

The sequences were described and sampled according to FAO (1990). The methods described in Porta *et al*. (1986) were followed for the physico-chemical analyses. Particle size distribution was obtained by wet sieving and the discontinuous sedimentation method, without removal of gypsum and carbonates. The fractions with diameters <2µm, 2-20µm, 20-50µm, 50-100µm, 100-250µm, 250-500µm, 0.5-1 mm and 1-2 mm were determined. Electrical conductivity and pH were measured in suspensions 1:5 and 1:2.5 (soil:water) respectively. Calcium carbonate equivalent was measured with a Bernard calcimeter. Gypsum equivalent was determined by precipitation of sulphates with barium chloride. Organic matter content was obtained through wet oxidation (Walkley-Black method).

Cation exchange capacity was determined with the NH_4Ac method at pH 7. Exchangeable cations were extracted with NH_4Ac and measured with Atomic Absorption.

2.3.4. Micromorphology and submicroscopy

Undisturbed blocks were taken from selected horizons of the sequences and vertical thin sections, 5x13 cm, were made following the procedures described in Benyarku and Stoops (2005), and were then studied using a polarising microscope, according to the guidelines of Stoops (2003).

Selected samples of the sands and coarse silts produced by wet sieving were studied under the binocular and the microscope using incident light, using x20, x40 and x100 magnifications. As well as the mineralogy, special attention was paid to the sand morphology.

The sand fractions from three outcrops from the Almenara area were prepared and their surfaces observed using electron microscopy. For the preparation of samples the methodology and criteria of Krinsley and Doornkamp (1973), were followed. Organic matter was removed with H_2O_2 and the coarse (2000-500 µm) and fine sand (500-50 µm) fractions were obtained by wet sieving, using the methods described by Porta *et al*. (1986). The sands were decarbonated with HCl 2N, by gradual dissolution with distilled water. Free iron oxides were removed with citric acid 1N and heavy and light sands were separated according to the methods of Stoops (1987).

About 25 quartz grains of fine sand, larger than 200 microns in diameter were selected with the help of a binocular, as these particles allow easier identification of forms of abrasion. The quartz grains were mounted in supports with double sided adhesive and coated with carbon before observation under a Scanning Electron Microscope, in secondary electron mode.

2.3.5. OSL dating

Sampling and pretreatments

Six samples were taken from selected sites, located in Figures 2.2 and 2.3 and described in Table 2.1 and 2.2.

Table 2.2. Location and additional characteristics of the samples for OSL dating

Location	ref	Moisture (g/100g)	Z (m)
Guiamets	GMT1	10,58	177.5
Guiamets	GMT2	3,75	179
Mas de l'Alerany, lower sequence	MAS1	8,69	248
Mas de l'Alerany, upper sequence	MAS2	9,94	256
Batea	BAT1	5,37	393
Almenara	ALM1	9,76	300

OSL samples were taken in daylight, after which the outer layers were removed and all further work was conducted under subdued orange light. The 63 – 100 µm grain size fraction was isolated in each sample, and treated with 32 % hydrochloric acid (HCl) to remove carbonates and 30 % hydrogen peroxide to remove any organic component. The quartz fraction was isolated following density separation using LST at δ = 2.70 and 2.58 g cm^{-3}, after which it was etched in 40 % HF for 1 hr, and finally immersed in HCl to remove fluorides. Machine apparatus was as described in Lowick and Preusser (2011). For dose rate calculations, the specific activities of U, Th, and K were determined using high-resolution gamma spectrometry (cf. Preusser and Kasper, 2001). Each sample was analysed for radioactive disequilibrium (Zander *et al.*, 2007), and no evidence was found for disequilibrium. Present day water content was measured using standard laboratory procedures (oven dry at 105ºC for 24h).

OSL characteristics

All estimated dose (D_e) measurements were made using the SAR protocol (Table 2.3). A preheat temperature of 240°C was chosen, following dose recovery and preheat tests (Fig. 2.4); this was held for 10 s and was also applied to all test doses. Dose recovery tests and recycling ratios were within 10% of unity for all samples, and confirmed the ability of the protocol to correct for any change in sensitivity of the sample (Wintle and Murray, 2000). Recuperation remained < 5 % of the natural signal for most aliquots IR stimulation for 100s at 50 °C was inserted before measurement of the second recycle point (Step 3^b, Table 2.3) to determine an IR depletion ratio with which to monitor the presence of feldspar contamination (Duller, 2003). A threshold of 0.80 was set, below which the OSL signal was not dominated by a quartz signal, and aliquots below this value were rejected.

Table 2.3. Modified SAR protocol (Murray and Wintle, 2003) applied to the coarse grain quartz fraction of all samples

Step	**Treatment**	**Observed**
1	Give dose[a]	
2	Preheat 240 °C for 10 s	
3[b]	IR stimulation for 100 s at 50°C	
4	Blue stimulation for 60 s at 125°C	
5	Give test dose	L_n or L_x
6	Preheat 240 °C for 10 s	
7	Blue stimulation for 60 s at 125°C	
8	Return to 1	T_n or T_x

[a] For Ln this is 0
[b] Only applied for second recycle point

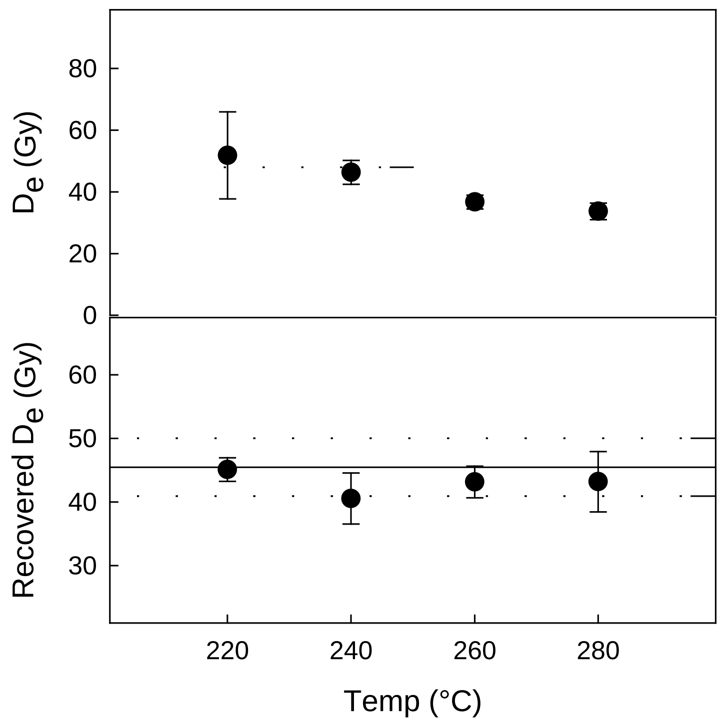

Figure 2.4. Preheat (top) and dose recovery (bottom) tests applied to MAS2 and GMT1 respectively. Temperatures from 220 to 280°C were applied in order to identify the appropriate temperature at which D_e was seen to be independent. For the dose recovery test a regenerative dose of 45 Gy was applied. Dashed lines represented 10 % errors

An example of the dose response curve (DRC) and an OSL decay curve for sample ALM1 is shown in Figure 2.5, and confirms that the quartz signal displayed a rapid decay, confirming domination by the fast component. Quartz D_e values were determined using the first 0.4 s of the OSL decay curve, and subtraction of a late background calculated using the last 10 s. The quartz OSL dose response fitted best to a saturating exponential plus linear function, which was used to determine D_e values.

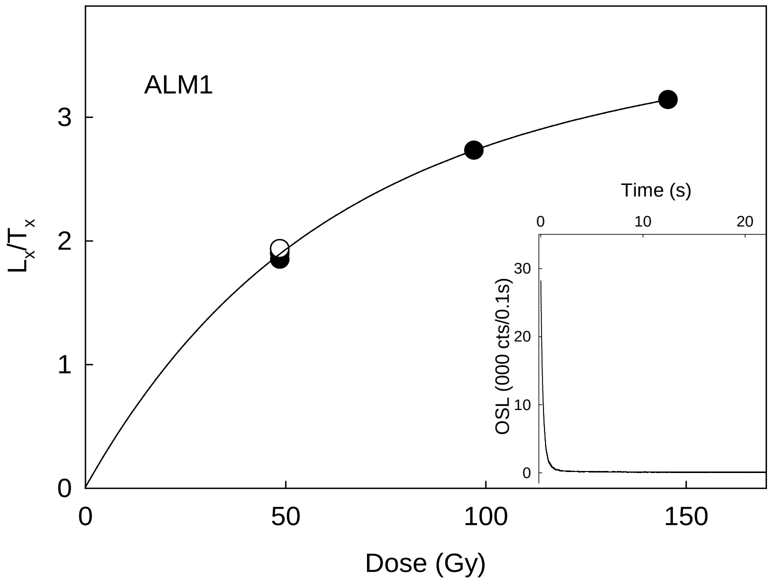

Figure 2.5. Dose response curve for sample ALM1 together with the decay curve of a natural signal (inset). Empty circle indicates the recycle dose point. This behaviour is representative of all samples

2.4. Results

2.4.1. General characteristics of the deposits

These deposits are predominantly composed of sands and silts, very homogeneous in size, and of a pale ochre colour, with the main characteristics presented in Table 2.4. They are vertically stable,there are no sedimentary structures, they do not have erosion patterns at their bases and their colour does not change vertically. Their slopes are very stable in spite of the low cohesion of the grains. They are very homogeneous sequences of very fine sands and silts, locally called “panal” (honeycomb), because the slopes of the outcrops have many flying insect holes that give the appearance of wasp nests.The sands and silts are composed of quartz grains (40-45%), calcite (28-45%), feldspars (2%), muscovites and biotites (4-10 %), iron oxides (2%), clinochlorite and other accessory minerals (<2%). The deposits are calcareous, poor in organic matter and have a mainly basic reaction. Some outcrops, out of the Móra basin contain gypsum (up to 28% in some samples, Table 2.4) and, in general, some more soluble salts (Abellà, 2011). They contain no animal remains, or bioturbation, except for the presence of tunnels. Occasional remains of gasteropod shells can be found. Bulk density values range between 1 350 and 1 450 kg m^{-3},although they remain very porous material with low cohesion in the presence of water erosion, except for some cases where the remobilisation of carbonates has slightly cemented some grains.

Table 2.4. Main characteristics of the loessic materials in the lower Ebro area (data from 29 samples, Abellà, 2011)

	Colour (moist) *	pH 1:2.5	CE 1:5 dS/m 25ºC	$CaCO_3$ eq. %	OC %	Gypsum %
Average	10YR 5/4	8.4	1.1	38.5	0.056	3.2
Standard Error	-	0.4	1.3	5.7	0.055	6.9
Max	-	8.9	4.3	51.0	0.285	28.6
Min	-	7.8	0.1	17.0	0.006	0.0

	Particle size distribution (sizes in µm, weight %)							
	<2	**2-20**	**20-50**	**50-100**	**100-250**	**250-500**	**500-1000**	**1000-2000**
Average	11.6	17.7	31.0	30.3	6.8	1.3	0.7	0.5
Standard Error	2.1	4.5	6.9	9.0	4.3	2.2	1.4	1.2
Max	16.1	25.6	40.1	47.9	24.1	9.9	7.6	6.6
Min	8.3	8.6	15.5	16.0	2.4	0.1	0.1	0.1

*mode

The best preserved aeolian materials (primary loess) are found on high platforms and dominant landforms in general. Reworking and later accumulation of these materials give rise to many slope and valley-bottom deposits (loess-like or secondary loess), with the latter being more clayey and silty than the primary ones. The windward deposits predominate, either on valley headwaters, or on the footslopes of prominent reliefs, where the thickest sequences are found.

2.4.2. Sand morphoscopy and SEM

Overall, no differences are observed between the different samples under the binocular (Fig. 2.6). All particles are rounded and have a similar mineral composition. Quartz is distinguished by being completely transparent, and always has impact features and micropolished surfaces, that can be attributed to collision between particles during wind transport in suspension. Samples have high contents of calcium carbonate, which may be the binding agent of the particles. Calcite forms aggregates or can be found as individual sparite grains. Other minerals include white feldspars, dark red iron oxides, greenish mica flakes and greenish-gray pyroxenes.

Under the SEM, none of the samples show the typical quartz morphology of loess grains. All samples show a mixture of large, more or less angular grains, together with typically aeolian rounded grains with impact features (upturned plates and concoidal fracture surfaces) (Culver *et al*., 1983), as well as grains with V-shaped features due to dissolution, indicating some sort of reworking from primary deposits by wind (Fig. 2.6).

Dissolution / reprecipitation of silica has occurred in almost all samples, and may mask some impact morphologies, or, in some other cases, rounded edges due to dissolution may be interpreted as of aeolian origin. While this process is typical of aeolian sedimentary environments, it cannot be considered exclusive, and it is therefore not diagnostic of these materials. In other cases, since its deposition during the Quaternary, these materials have been reworked from some positions and mixed with alluvial sands and clays. The same wind morphologies are displayed depending on the intensity of the processes and the transport distance, which can be variable. While there are no typical aeolian samples, in almost all samples there are some typical aeolian features. All deposits can be interpreted as material that has undergone several cycles of sedimentation by either wind or water.

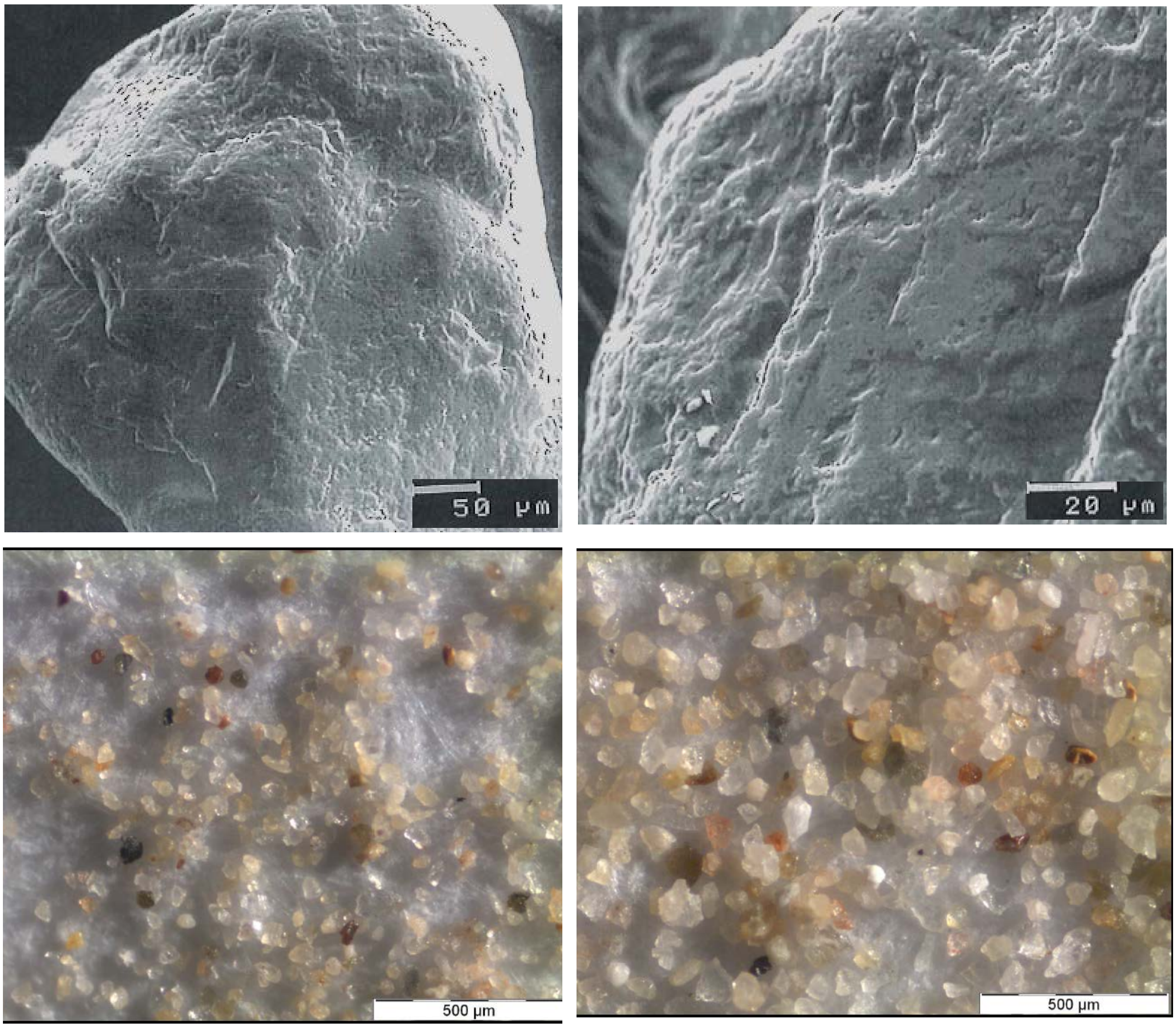

Figure 2.6. SEM images (secondary electron mode) of fine sand morphology of samples from the Almenara area (upper). Binocular images of coarse silt (lower left) and very fine sand (lower right) of samples from the Flix area

2.4.3. Morphology of the studied sequences

All studied sequences are formed by primary loess. Three outcrops (Batea, Guiamets, Almenara) are formed by a single sequence, and two of them (Tivissa and Mas de l'Alerany) are formed by two sequences each (upper and lower).

The morphology of the profiles (Tables 2.5 and 2.6) indicates that besides formation of structure, secondary carbonate redistributions are found in all profiles, in particular in the Tivissa profile (lower sequence), where large rhizocretions reach almost 50% of the volume of some horizons. Mas de l'Alerany also shows a large calcium carbonate accumulation. Other forms are nodules and queras. The latter are distinguished from pseudomycelia as they are thicker, similar to vermiform gypsum, lack a powdery appearance –are formed by sparite grains- and do not react with $BaCl_2$.

Gypsum redistribution is observed in the Batea and Almenara profiles. The morphologies are similar in both cases: they appear mainly at the bottom half of the sequences, as vermiform gypsum and as large gypsum crystals.

The lower section of Mas de l'Alerany (MAB1, Table 2.5) is rubefied (2.5YR hues), and shows recarbonatation on a former Bt horizon, which indicates that this profile is much older than the rest. Although remains of a decarbonated horizon are present, this profile is most probably truncated.

Table 2.5. Main morphological characteristics of the Mas de l'Alerany, Almenara and Guiamets profiles

Profile	Horizon	Depth (cm)	Colour (moist)	Structure	Accumulations
Mas de l'Alerany MAB1	Ap	0-28	5YR 5/6	Strong subangular blocky	None
	$2Btk_1$	28-54	2.5YR 4/4	Strong subangular blocky	Frequent nodules-rhizocretions- of carbonates, >2cm, vertical
	$2Btk_2$	54-110	2.5YR 5/4	Strong subangular blocky	Abundant nodules-rhizocretions- of carbonates, >2cm, vertical
	$2Btk_3$	110-164	2.5YR 5/4	Strong subangular blocky	Generalized nodules-rhizocretions- of carbonates, >2cm, vertical
	$3Bk_4$	164-222	10YR 7/4	Massive	Frequent nodules-rhizocretions- of carbonates, >2cm, vertical
	$4Bwk_5$	222-278	10YR 7/4	Moderate, due to faunal activity	Very abundant nodules-rhizocretions- of carbonates, >5cm, vertical
	$5Bwk_6$	278-315	10YR 7/4	Weak, granular, due to faunal activity	Generalized nodules-rhizocretions- of carbonates, >15cm, vertical
Mas de l'Alerany MAB2	Ap+Bw	0-140	10YR 4/4	Massive	Carbonate pseudomycelia
	Bw	140-212	10YR 7/6	Massive	Carbonate pseudomycelia, coatings and nodules (<1%)
	2Btk	212-242	2.5YR 6/4	Massive	Carbonate nodules, 20-50%
Mas de l'Alerany MAB3	$4Bwk_5$		10YR 7/4	Moderate, due to faunal activity	Very abundant nodules-rhizocretions- of carbonates, >5cm, vertical
	6Bw			Massive	None
Guiamets	Ap	0-26	10YR 5/4	Moderate, subangular blocky, medium.	None
	Bkn	26-103	10YR 5/4	Moderate, subangular blocky, medium. Secondary: weak, due to faunal activity	Carbonate pseudomycelia and friable nodules, 15-20% (vol)
	Bwk_1	103-175	10YR 5/4	Weak, subangular blocky, medium.	Carbonate pseudomycelia, <10% (vol)
	Bwk_2	175-280	10YR 5/4	Moderate, subangular blocky, coarse. Secondary: weak, due to faunal activity	Carbonate pseudomycelia, 2-5% (vol)

Table 2.5. Main morphological characteristics of the Mas de l'Alerany, Almenara and Guiamets profiles (cont.)

Profile	Horizon	Depth (cm)	Colour (moist)	Structure	Accumulations
Almenara	Ap_1	0-10	10YR 5/4	Weak, crumb, fine	none
	Ap_2	10-22	-	-	-
	Bw_1	22-84	10YR 6.5/6	Weak, subangular blocky, coarse; due to faunal activity	none
	Bw_2	84-134	10YR 6.5/6	Weak, subangular blocky, coarse; due to faunal activity	none
	Bwy_3	134-174	10YR 6.5/6	Weak, subangular blocky, coarse; due to faunal activity	Vermiform gypsum, few
	$2Bwy_3$	174-206	7.5YR 5/4	Weak, subangular blocky, coarse; due to faunal activity	Vermiform gypsum, frequent
	$2Bwy_4$	206-236	7.5YR 5/4	Weak, subangular blocky, coarse; due to faunal activity	Vermiform gypsum, frequent; and gypsum roses, frequent
	$2Bwy_5$	236-272	7.5YR 6/6	Weak, subangular blocky, coarse; due to faunal activity	Vermiform gypsum, frequent; and gypsum roses, few

Table 2.6. Main morphological characteristics of the Tivissa and Batea profiles

Profile	Horizon	Depth (cm)	Colour (moist)	Structure	Accumulations
Batea	Ap	0-40	10 YR 5/4	Subangular blocky, fine	None
	Bw	40-240	10 YR 5/4	Subangular blocky, fine	None
	Bw	240-350	10 YR 4/4	Subangular blocky, fine	None
	Bwy	350-400	10 YR 6/5	Subangular blocky, coarse	Vermiform and gypsum roses, >20% (vol.)
	Bwy	400-450	10 YR 6/5	Subangular blocky, coarse	Vermiform and gypsum roses, 2-20% (vol.)
	Bw	450-500	10 YR 5/4	Subangular blocky, coarse	None
	Bwy	500-550	10 YR 6/4	Subangular blocky, fine	Vermiform < 2% (vol.)
	Bw	550-650	10 YR 5/4	Subangular blocky, fine	None
	Bw	650-750	10 YR 5/4	Subangular blocky, coarse	None
	Bwy	750-850	10 YR 6/4	Subangular blocky, coarse	Vermiform (gypsum), 2-20% (vol.)
	Bwy	850-900	10 YR 4/4	Subangular blocky, fine	Vermiform (gypsum), <2% (vol.)
Tivissa TIV-1	Ap	0-300	10 YR 4/4	Subangular blocky	Queras, <2%
	Bwkn	30-100	10 YR 6/5	Subangular blocky	Large rhizocrecions (nodules), queras , 20-40%
	Bwkn	100-200	10 YR 6/4	Subangular blocky	Id. > 40%
Tivissa TIV-2	Ap	0-30	10 YR 4/4	Subangular blocky, medium	Carbonate nodules, queras <2%
	Bw	30-50	10 YR 6/4	Subangular blocky, medium	Queras 2-20%
	Bwk	50-100	10 YR 5/4	Subangular blocky, medium	Small carbonate nodules and queras >20%
	Bwk	100-150	10 YR 6/4	Subangular blocky, medium to coarse	Carbonate nodules and queras >20%
	Bw	150-200	10 YR 6/4	Subangular blocky, medium to coarse	Queras, 0-20%
	Bw	200-250	10 YR 5/4	Subangular blocky, medium	None
	Bw	250-400	10 YR 6/4	Subangular blocky, medium to coarse	Queras, <2%
	Bw	400-500	10 YR 6/4	Subangular blocky, coarse	Queras, 2-20%
	Bw	500-600	10 YR 6/4	Subangular blocky, coarse	None
	Bw	600-800	10 YR 6/4	Massive	None

2.4.4. Particle size

The texture of the deposits varies widely from sandy loam to loam and silt loam (Fig. 2.7a and 2.8, Table 2.7). All sequences show similar particle sizes, with the most common particle-size fractions being: very fine sand (50-100 µm; 36% in weight), coarse silt (20-50 µm; 25% in weight), fine silt (2-20 µm; 15% in weight), and clay (<2 µm; 13% in weight). While the sequences at Batea and Tivissa are the coarsest, and those at Almenara finest, the vertical variation of the grain size distribution is of the same order of magnitude in all samples studied, making it difficult to establish a spatial particle-size pattern that could help to elucidate the source area of the materials. The vertical variation does not follow the same trend in all profiles (Fig. 2.8, Table 2.7). Batea and Guiamets coarsen upwards, while Tivissa (both sequences) coarsen downwards. Almenara and Mas de l'Alerany do not show any definite pattern.

In the sites with more than one sequence (Tivissa and Mas de l'Alerany), the more recent one tends to be coarser than the older one (Fig. 2.7b), and could indicate a higher transport capacity, and/or a higher aridity. These materials, according to their size characteristics, are coarser than the classical loess and correspond to what some authors have called 'sandy loess' (Coudé - Gaussen, 1987 and 1990).

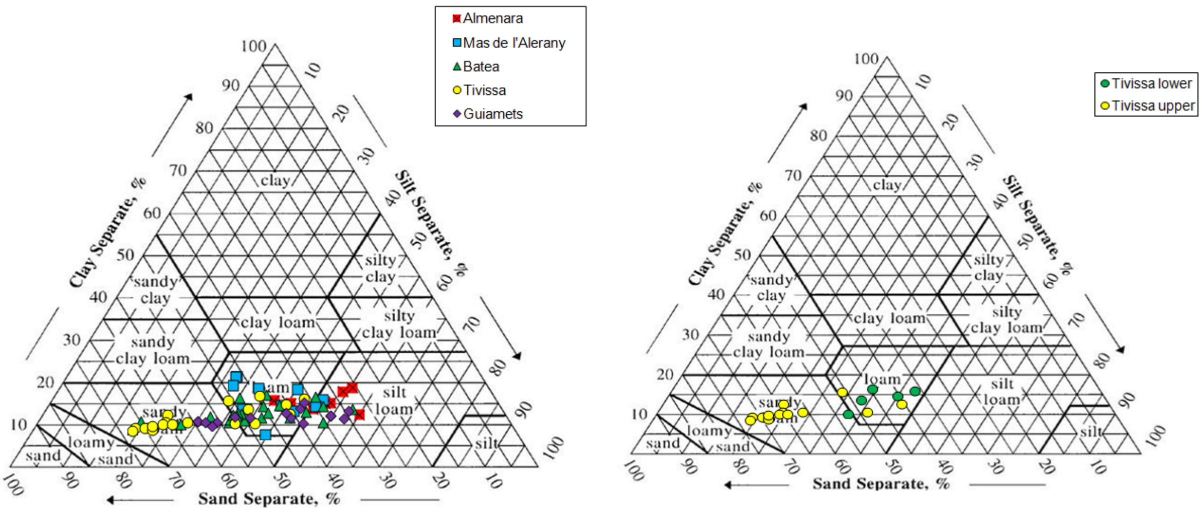

Figure 2.7. Texture classes of the selected sequences. (a) whole set of samples of the 5 selected areas and (b) Tivissa upper and lower sequences

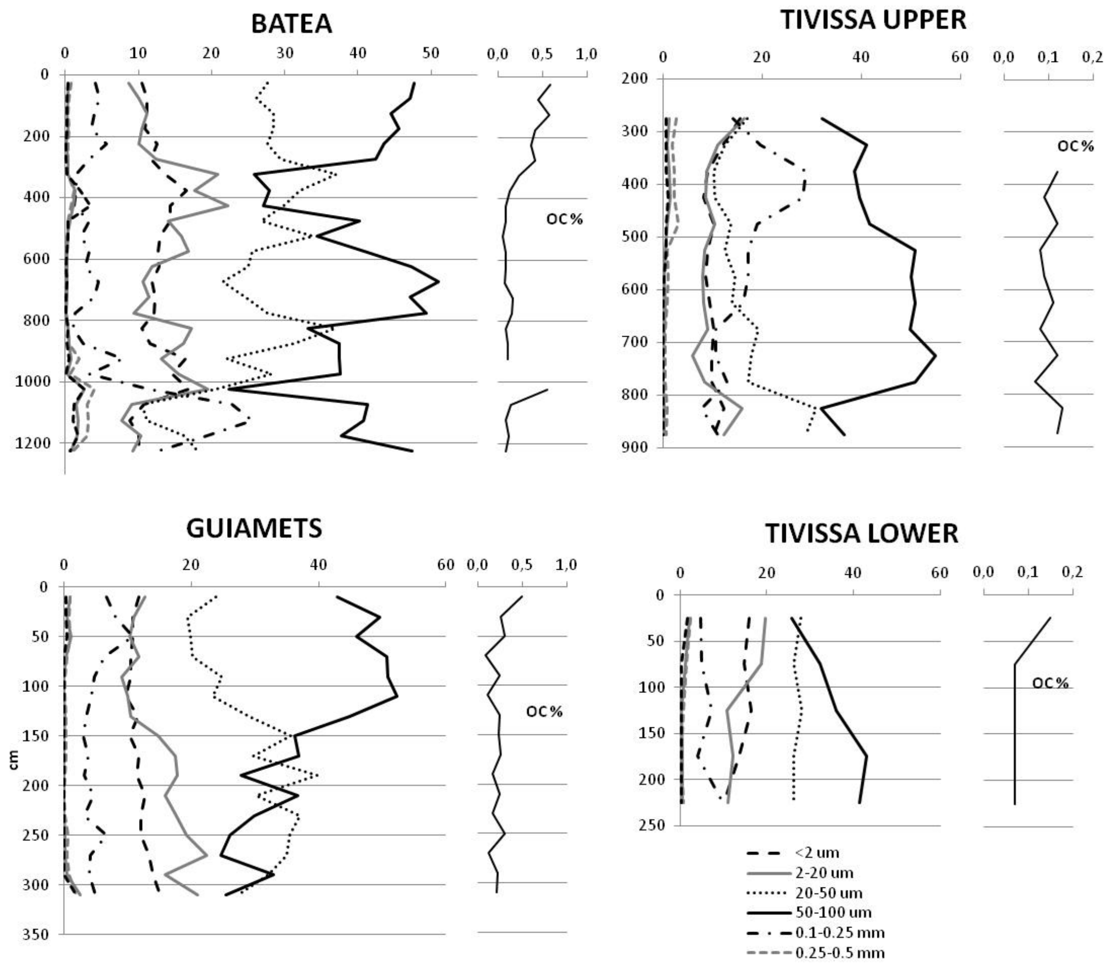

Figure 2.8. Particle size distribution and OC profiles in four of the studied sites. Horizontal axis are weight percentages, vertical axes are cm

2.4.5. Soil reaction, calcium carbonate, gypsum, organic matter content, cation exchange capacity and exchangeable cations

The chemical characteristics of the profiles Mas de l'Alerany and Almenara are presented in Table 2.9. They mostly have a basic soil reaction, and in some cases are alkaline. They have very high content of calcium carbonate (32-46 weight %). No decarbonation is evident, except for the upper horizons of Mas de l'Alerany (Ap and 2Btk), where a decrease in calcium carbonate is observed in comparison with the underlying materials. Organic matter is low (0.1-0.5%). There are some cases where an increase is observed, pointing to periods of pedogenesis during loess deposition (Batea, Tivissa lower, Guiamets, Fig. 2.8).

Table 2.7. Particle size distribution of the Mas de l'Alerany (MAB) and Almenara (ALM) profiles

Sample	Horizon	Particle size distribution (sizes in ìm, weight %)							
		<2	2-20	20-50	50-100	100-250	250-500	500-1000	1000-2000
MAB-1/1	Ap	7.5	20.3	24.4	29.2	14.7	1.9	1.0	1.0
MAB-1/2	$2Btk_1$	21.3	17.7	14.5	20.4	11.6	4.2	3.4	6.9
MAB-1/3	$2Btk_2$	21.2	14.8	17.4	16.6	15.8	4.6	3.4	6.2
MAB-1/4	$2Btk_3$	19.2	11.2	21.5	21.7	16.9	3.6	2.9	3.0
MAB-1/5	$3Bk_4$	18.4	7.3	30.5	21.8	14.1	3.0	2.9	2.0
MAB-1/6	$4Bwk_5$	14.4	18.3	25.9	19.3	10.5	4.0	3.6	4.0
MAB-1/7	$5Bwk_6$	15.7	23.0	28.4	7.3	17.2	3.2	2.5	2.7
MAB-2/1	Ap-Bw	13.6	17.4	20.5	25.3	18.7	2.6	1.5	0.4
MAB-2/2	Bw	13.5	15.0	22.3	28.8	17.4	1.8	1.0	0.2
MAB-2/3	2Btk	18.2	24.8	20.5	16.1	7.6	5.1	3.7	4.0
MAB-3/1	$4Bwk_5$	14.3	16.0	34.7	25.5	7.0	1.2	0.7	0.6
MAB-3/2	6Bw	13.2	14.6	32.6	27.7	11.0	0.5	0.3	0.1
89-ALM-1/1	Ap_1	13.6	19.6	30.9	28.6	5.3	1.3	0.4	0.3
89-ALM-1/2	Ap_2	15.0	22.0	30.1	28.1	3.9	0.5	0.3	0.1
89-ALM-1/3	Bw_1	15.5	25.5	26.2	28.0	4.3	0.3	0.2	0.0
89-ALM-1/4	Bw_2	15.1	25.1	28.0	25.9	5.1	0.5	0.2	0.1
89-ALM (OSLC)	Bwy_3	15.6	19.1	23.0	37.6	3.5	0.5	0.3	0.4
89-ALM-1/5	Bwy_3	14.9	16.9	28.7	34.0	4.6	0.6	0.2	0.1
89-ALM-1/6	$2Bwy_3$	12.2	29.2	30.8	16.5	6.0	3.3	1.3	0.7
89-ALM-1/7	$2Bwy_4$	18.7	27.2	28.2	15.6	5.5	3.2	0.9	0.7
89-ALM-1/8	$2Bwy_5$	17.8	27.1	26.9	18.0	6.5	3.0	0.5	0.2

Cation exchange capacity is low (5-7 cmol(+)/kg) in the subsurface horizons, and is in good agreement with the low amount of siliceous clay and their micaceous nature (data not presented). Calcium is the dominant cation but in some cases magnesium is dominant, as is the case in Almenara (Table 2.8), indicating the presence of magnesium rich salts in the dust deposits.

Many of the outcrops are gypsum free throughout ($EC_{1/5}$ < 0.2 dS/m at 25º C). However in some oucrops of the Ebro depression, noticeable amounts of gypsum are found at depth ($EC_{1/5}$ =2 dS /m at 25ºC) as in true loess deposits as Batea (data not presented) or Almenara (Table 2.8), but also in the loess-like ones. This gypsum is found in secondary forms (vermiform, gypsum roses and large crystals, Tables 2.5 and 2.6) in the loess. None of the studied deposits in the Móra d'Ebre basin contains gypsum.

Table 2.8. Main chemical characteristics of the Mas de l'Alerany (MAB) and Almenara (ALM) profiles

Sample	Horizon	pH 1:2.5	CE 1:5 dS/m 25ºC	$CaCO_3$ eq. %	Gypsum %	OC %	Exchange Complex (cmol(+)/kg)				
							CEC	Ca^{2+}	Mg^{2+}	K^+	Na^+
MAB-1/1	Ap	8.4	0.15	18	0	0.95	10.5	9.01	0.98	0.34	0.05
MAB-1/2	$2Btk_1$	8.7	0.12	32	0	0.30	10.9	10.05	0.65	0.16	0.08
MAB-1/3	$2Btk_2$	8.8	0.12	31	0	0.12	10.1	8.99	0.86	0.12	0.09
MAB-1/4	$2Btk_3$	8.8	0.12	24	0	0.12	10.7	9.29	1.15	0.12	0.11
MAB-1/5	$3Bk_4$	8.7	0.15	40	0	0.09	5.1	4.28	0.61	0.05	0.11
MAB-1/6	$4Bwk_5$	8.4	0.32	42	0	0.11	5.8	4.22	1.23	0.05	0.30
MAB-1/7	$5Bwk_6$	8.5	0.36	40	0	0.16	5.4	3.20	1.50	0.06	0.59
MAB-2/1	Ap-Bw	8.8	0.12	42	0	0.23	4.3	3.64	0.53	0.11	0.05
MAB-2/2	Bw	8.9	0.12	40	0	0.11	4.3	2.90	1.22	0.08	0.08
MAB-2/3	2Btk	8.8	0.15	43	0	0.14	7.8	4.56	2.99	0.07	0.19
MAB-3/1	$4Bwk_5$	8.8	0.11	38	0	0.09	4.7	3.40	1.08	0.20	0.05
MAB-3/2	6Bw	8.9	0.11	34	0	0.09	4.8	3.06	1.58	0.11	0.05
89-ALM-1/1	Ap_1	8.2	0.20	31	0.5	0.64	6.1	5.02	0.75	0.02	0.33
89-ALM-1/2	Ap_2	8.5	0.14	33	0.2	0.07	5.1	4.24	0.61	0.03	0.19
89-ALM-1/3	Bw_1	8.6	0.14	39	1.1	0.19	5.3	4.43	0.77	0.07	0.06
89-ALM-1/4	Bw_2	8.6	0.15	37	1.3	0.11	4.4	2.35	1.90	0.06	0.07
89-ALM (OSLC)	Bwy_3	8.5	0.31	33	0.0	0.15	3.7	0.33	2.96	0.26	0.13
89-ALM-1/5	Bwy_3	8.6	0.21	35	2.9	0.04	4.5	1.88	2.45	0.15	0.07
89-ALM-1/6	$2Bwy_3$	7.9	2.32	29	14.1	0.02	4.9	3.21	1.49	0.06	0.10
89-ALM-1/7	$2Bwy_4$	8.0	2.40	34	8.0	0.00	4.7	1.57	2.90	0.11	0.09
89-ALM-1/8	$2Bwy_5$	8.0	2.23	38	4.9	0.00	3.9	0.73	2.97	0.08	0.09

2.4.6. Micromorphology

The micromorphological study shows a striking uniformity in the groundmass of the materials, which consists of a very well sorted, very fine (Batea and Guiamets) or fine sand (Tivissa) composed of almost equal proportions of equant subangular quartz, rounded limestone grains and micritic rounded aggregates as groundmass, together with minor amounts of plagioclases, muscovite flakes and sparite. Some quartz grains are well-rounded and have matt surfaces, indicating a different origin. Porosity is mainly from highly connected packing pores, with total values ranging from 20 to 40% (visual estimation). The coarse/fine (c/f) ratio is about 3/1, and the b-fabric of the micromass is crystallitic, due to micrite as a product of weathering of the micritic limestone. The c/f related distributions are single spaced enaulic, to single spaced or close porphyric, depending on the degree of compaction of the parent material. Sometimes it is difficult to distinguish limestone grains from micrite aggregates or faunal excrements appearing as infillings in biopores, since they have the same diameter. In the Guiamets profile some redistribution of materials is evident in the first metre of the profile, evidenced by the presence of a few fragments of surface crusts with some degree of sorting, together with a loss of the original enaulic c/f related distribution of the aeolian material. The presence of such crust fragments suggest some periods of stability during the accretion of the deposit.

The soil formation processes consist of a redistribution of carbonates, mainly as orthic or disorthic impregnating nodules of micrite, up to 1 cm in Ø (Guiamets) or even up to several centimeters (Tivissa). The latter corresponds to the spectacular carbonate rhizocretions (loess dolls) described in the field (Table 2.6). A second form of carbonate redistribution are queras, i.e. compound pedofeatures of biosparite infillings in biopores surrounded by carbonate depletion hypocoatings (Herrero *et al*., 1992). They are very frequent in the upper Batea profile, and present in the rest of the samples. Sometimes they are disturbed by fauna, therefore some of the former biosparite infillings are found as sparite nodules in the groundmass. In other cases biosparite grains have undergone a partial dissolution process (Figure 2.9A, Batea profile), pointing to an ageing process of these biological pedofeatures.

The Tivissa profile contains frequent impregnating nodules of Fe-oxyhydroxides, orthic and irregular, which sometimes originate in a ferro-magnesian grain that acts as a nucleus. Although the materials are highly permeable and the profiles are well drained at present, the lack of structure and of preferential flow planes could be the cause of saturation in case of heavy rains or subsurface flows.

The lower Batea profile shows a strong accumulation of gypsum that appears as infillings and coatings of lenticular gypsum in biopores (Figure 2.9B), which correspond to the large gypsum crystals and gypsum roses observed in the field (Table 2.6). The internal fabric ranges from idiotopic to xenotopic. The loss of mixing of the loose infillings with the groundmass and the poor sorting of the gypsum crystals (from very fine to very coarse sand sizes) indicates that gypsum precipitated from a gypsum-saturated soil solution, most likely from the dissolution of gypsum in the upper part of the profile (Poch *et al*., 2010).

The lower Almenara profile also shows gypsum as xenotopic coatings and infillings of coarse gypsum in pores, and loose complete infillings of lenticular gypsum of fine sand size. It contains few nodules and infillings of micrite along cracks, together with compound packing pores that apparently contribute to a decrease in the total porosity (Figure 2.9C). Some of the carbonatic features seem to derive from highly disturbed queras (sometimes with the decarbonated areas still preserved); and also textural features such as intercalations and nodules (Figure 2.9D). Another conspicuous feature is a nodule (nest) of celestite (strontium sulphate) prisms (Figure 2.10A, B) at the base of the sequence.

The upper part of the oldest sequence of the Mas de l'Alerany profile has a rubefacted section (Btk horizons), that is due to a decarbonated micromass, partly recarbonated, composed of a reddish mixture of fine silt, clay, Fe oxi-hydroxides, and micrite in 75% of the volume of the micromass. Its b fabric is crystallitic micrite (75%) in the recarbonated patches, and stipple-speckled to undifferentiated in the decarbonated areas (25%). As pedofeatures, orthic and disorthic micrite nodules are abundant (Figure 2.10C), together with fine (0.2 mm thick) clay coatings, microlaminated, inside some fissures of the calcitic nodules. Layered coatings of micrite alternating with more clayey bands around nodules are also observed (Figure 2.10D). In the lower part of the sequence, which is unrubefacted (Bk horizons), the micromass is completely crystallitic micritic, but presents some microlaminated clay coatings and infillings illuviated from the overlying horizons (Figure 2.10E).

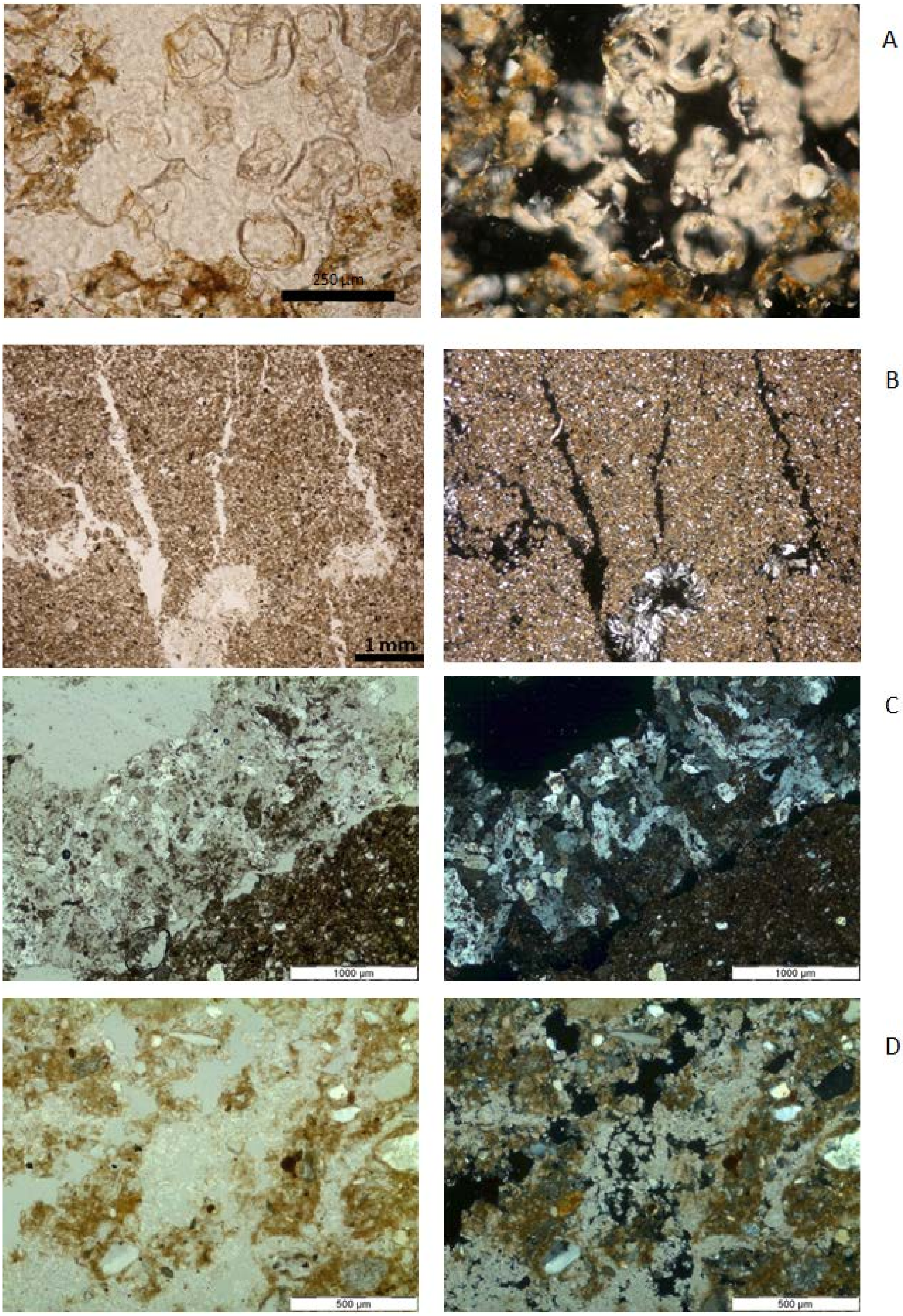

Figure 2.9. A: Partly dissolved citomorphic sparite grains in an aged quera. Batea profile, Bwk horizon. B: Fissures and coatings of hypidiotopic gypsum around pores. Batea profile, Bwy horizon. C: Coating of xenotopic gypsum in a pore wall, showing inclusions of micrite grains. Almenara profile, Bwy horizon. D: Loose discontinuous infillings of microsparite in pores, adjacent to decarbonated hypocoatings, probably old queras. Almenara profile, Bwy horizon. (PPL and XPL images)

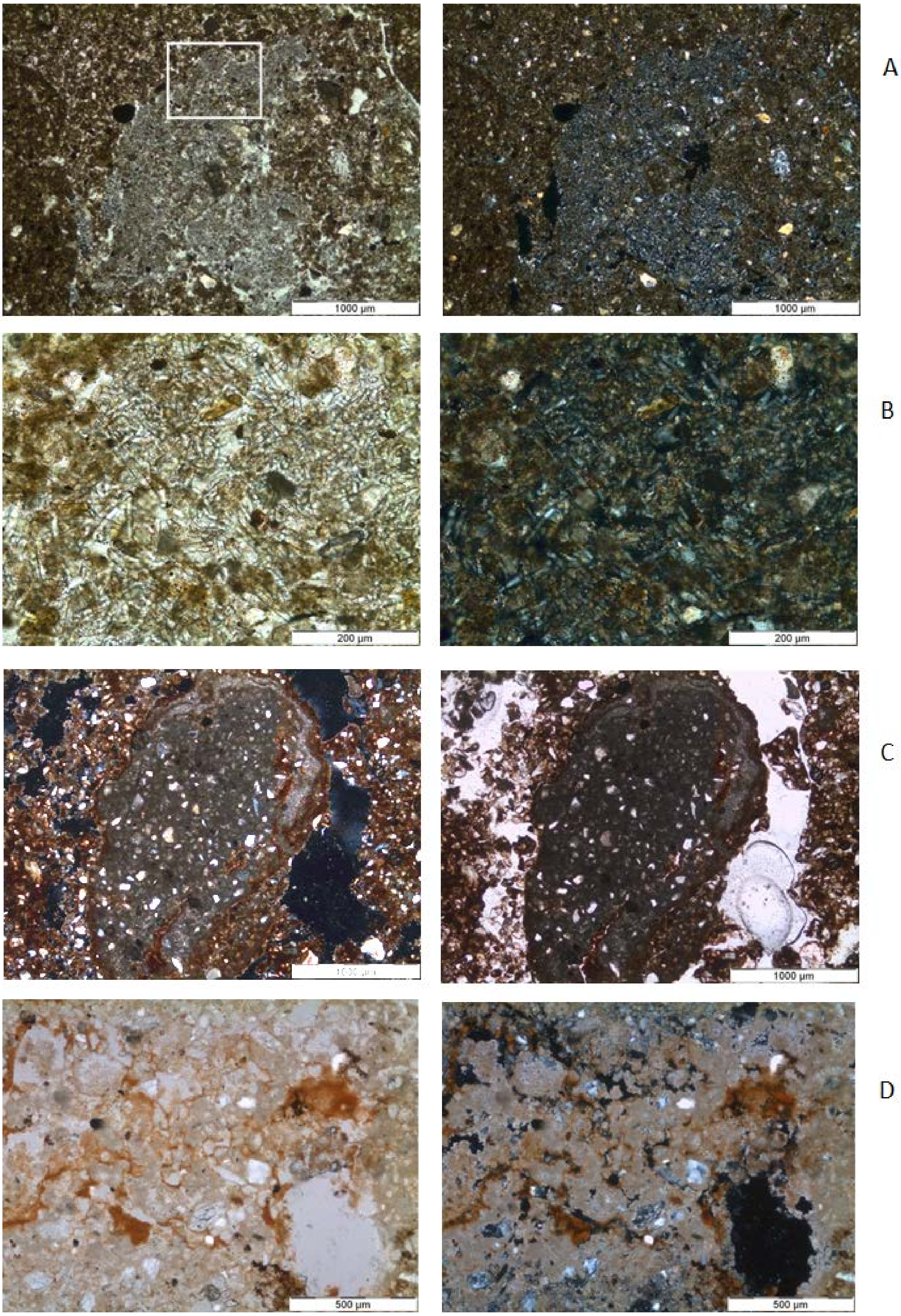

Figure 2.10. A and B: Nodule of celestite crystals, recognized by their rod shape, low anisotropy and high relief, Almenara profile, Bwy horizon. C: Orthic nodule of micrite, with alternating coatings of clay and micrite, Mas de l'Alerany profile, horizon $2Btk_1$. D: Clay coatings and infillings within a micritic groundmass, Mas de l'Alerany profile, horizon $4Bwk_5$. (PPL and XPL images)

2.4.7. Dating

Ninety percent (90 %) of all aliquots measured passed the performance criteria, and the rapid decay of stimulation curves confirmed the identification of the fast component. To confirm that the OSL signal was not close to saturation, $2D_0$ (85 % saturation of the signal) was calculated by fitting DRCs to a single saturating exponential, and were between 2 – 300 Gy. Except for MAS1, all samples returned D_e values below this range, confirming that saturation of the signal was not a problem (Wintle and Murray, 2006). The as-measured water content was taken as representing the average moisture of the samples over time, and also to reflect well the variation between different depths. It should be noted that a 10 % underestimation of water content over time would result in a 10 % underestimation in age. D_e values and ages are reported in Table 2.9, together with the dosimetric data. As all samples were identified as loess, this wind-blown sediment would have been exposed to daylight long enough to ensure complete zeroing of the sample, prior to burial, and this is confirmed by over-dispersion values of between 5 and 13 % for the D_e distributions of all samples, except for MAS2. For this reason, D_e values were calculated using the Central Age Model (CAM) (Galbraith *et al*., 1999). The overdispersion of 24 % for the distribution of MAS2 however, was slightly wider but, as deposition is considered to be very similar to the other samples, the larger spread may rather be explained by the presence of occasional carbonate nodules found in this profile, which would generate a dosimetric heterogeneity between grains, and so the application of the CAM was still considered most appropriate for this sample. All OSL ages were in stratigraphic agreement and (excluding MAS1) gave ages between 17 and 34 ka. The SAR protocol (Murray and Wintle, 2000) has proved very successful when dating quartz (Murray and Olley, 2002; Wintle and Murray, 2006), and often provides ages beyond the last interglacial (Dehnert *et al.,* 2012; Pawley *et al.,* 2008; 2010). Beyond 70 ka, and D_e values above 150 – 200 Gy however, problems have been reported at some sites, where independent dating has shown the quartz OSL to underestimate, despite the methods meeting all the standard criteria set for testing the performance of the SAR protocol (Wintle and Murray, 2006), (Lai, 2010; Lowick *et al*., 2010; Timar *et al*., 2010). Except for MAS1, D_e values for all samples remained below 100 Gy and well below saturation, and so the OSL ages for the younger samples are considered reliable. MAS1, returned a much older age of 115 ± 7 ka, derived from a central D_e value of 225 Gy. While there is no evidence to suggest a problem with the quartz signal, two aliquots of this sample were rejected for having values of > 300 Gy, and close to saturation of the signal. The age for MAS1 should therefore be considered only a minimum possible age.

These ages are consistent with those of the fluvial terraces, since loess deposits cover some parts of the second Ebro terrace at Flix (considered upper Pleistocene); but are not found on the first terrace (Holocene). However, more than one depositional cycle is suggested by the various degrees of weathering shown by these materials, as well as the OSL age of MAS1 for the lower sequence of Mas de l'Alerany.

Table 2.9. Dosimetry information, water content, D_e values and calculated ages. Concentrations were converted to infinite matrix dose using the standard conversion factors of Adamiec and Aitken (1998). Cosmic radiation contribution was calculated using present day sample burial depth following Prescott and Hutton (1994), and attenuation factors were taken from Mejdahl (1987). a-value 0.01 ± 0.02. n is the number of individual aliquots contributing to the De value against the number of aliquots measured. An uncertainty of 20 % was added to present day water content to accommodate changes over time. All errors are calculated in quadrature, and are reported to one standard error on final OSL ages

OSL Sample	Mineral fraction(µm)	n	Radionuclide concentration			Dose rate (Gy ka^{-1})	Water (%)	Over-dispersion n	D_e (Gy)	Age (ka)
			^{238}U (ppm)	^{232}Th (ppm)	^{40}K (%)					
MAS1	63-100	22/24	1.70 ± 0.15	6.70 ± 0.22	1.00 ± 0.01	1.95 ± 0.09	11	11	225.4 ± 6.3	115.6 ± 6.1
MAS2	63-100	24/24	1.68 ± 0.36	6.55 ± 0.21	0.92 ± 0.01	1.89 ± 0.09	4	24	44.6 ± 2.2	23.6 ± 1.6
GMT1	63-100	24/24	3.48 ± 0.21	7.33 ± 0.27	1.05 ± 0.02	2.10 ± 0.10	9	10	65.7 ± 1.4	31.3 ± 1.7
GMT2	63-100	34/34	1.70 ± 0.56	7.59 ± 0.11	1.08 ± 0.02	2.33 ± 0.09	10	13	53.6 ± 2.0	23.8 ± 1.4
ALM1	63-100	22/24	1.69 ± 0.41	8.61 ± 0.22	1.29 ± 0.02	2.50 ± 0.12	5	11	85.6 ± 2.2	34.2 ± 1.8
BAT1	63-100	33/34	1.43 ± 0.23	6.49 ± 0.26	0.92 ± 0.02	2.00 ± 0.09	10	5	35.7 ± 0.9	17.9 ± 0.9

2.5. Discussion

2.5.1. Hypothesis on the possible source areas

The factors used here to explain the possible provenance of the loess are (1) spatial distribution of the outcrops in the whole area, (2) thickness, (3) position wind- or leeward referred to the orographic traps, (4) particle size distribution and (5) composition and micromorphology.

Although the distribution of the outrops is very heterogeneous, the most important group, in extension and thickness, is found at the Lower Ebro Valley, especially in the Móra Basin (areas 1 to 4, Fig. 2.1b). The distribution is very well adapted to the footslopes of transversal prominent ranges and to the corridor created by the Ebro River. It is likely that the rest of the outcrops (areas 5 to 7, Fig. 2.1b) were less preserved because of the more gentle relief in the headwaters of the Segre tributaries, that create a “less efficient trap” effect than in the first case. The thickest outcrops are also found at the eastern margins of the Ebro Depression and the footslopes of the most prominent coastal ranges, while the second group (areas 5 to 7, Fig. 2.1b) are thinner. The outcrops are windward, if we consider a WNW prevalent wind. It should be kept in mind that when annual dust deposition is smaller than 0.5 mm for long periods of time, the dust becomes integrated in the soils and no loess deposits occur (Yaalon, 1987), but recent research (Crouvi *et al*., 2009) demonstrates that much lower rates of dust accretion also allow loess formation. Also, very intensive land levelling, terracing and erosion (Boixadera *et al*., 1987) in the region, have contributed to eliminating the thinner deposits.

The textures are very coarse for a loess and suggest, according to most authors (Simonson and Hutton, 1954; Pye, 1995; Muhs *et al*., 2004), that the source areas are very proximal -as a flood plain-, and up to the order of tens of km away. There are no sand deposits upwind of the loess outcrops, nor have they been mentioned in any soil or geological report, and so in this case, the source material is not sand dunes as occurs in the proximal loess deposits from Neguev desert (Yaalon and Dan, 1974; Crouvi *et al*., 2008), at Matmata Plateau (Coudé-Gaussen, 1990) or in other cases in North, central or South Africa, Arabia or Middle East where they are clearly due to a process of aeolian abrasion from sand dunes or active sand seas (Crouvi *et al*., 2010). Loess in the Tagus valley contains more than 20% clay -and is therefore finer than our study area-, with their origin being the fine alluvial material accumulated in the valley (García-Giménez *et al*., 2012). In our case, rather than texture, the predominant indicators of source area are the prevalent wind direction, the proximity to the deposits and the presence of gypsum and magnesium.

The mineralogical composition of the loess (about 40% quartz, 40-50% calcium carbonate), supports the source areas in the same sense, in the frame of the Ebro valley. Proximal flood plains (Ebro and Segre Rivers) and alluvial fans (Ondara and Corb Rivers) are the main sources for the carbonaceous and quartz materials. The lack of generalized aeolian features in the sand quartz grains also points to a short transport.

Absence or presence of gypsum may be an important indicator of specific sources. Although it is considered to be a rare component in loess (Mestdagh *et al*., 1999) it has been found in several loess areas in the world (García-Giménez *et al.*, 2012). In our case it is present in only a limited amount (up to 28% in some areas or absent in others) as gypsum (anhydrite is not a stable mineral under subaeral exposures, neither under the present climatic conditions (Herrero and Porta, 2000)). Gypsum analysis is difficult (Herrero *et al*., 2009) and results are often misleading: small amounts are difficult to ascertain in routine analysis and $EC_{1:5}$ can give results that are not easy to interprete where salts more soluble than gypsum are present. For this study, gypsum is present in parts of Almenara and Batea sequences. Significant amounts are also found in loess-like deposits in the Lower Ebro Valley but appear to be absent in the Móra basin. Gypsum is much more soluble than calcium carbonate and in humid climates it is easily leached from soils and landscapes, but in arid and semiarid regions it remains in the soil (Herrero and Porta, 2000). In our true loess (Batea and Almenara sequences), gypsum is only found in significant amounts in the lower part of the profiles and this is probably an indication of gypsum being present in the original dust, and of a later redistribution. In loess-like deposits a mixed origin is envisaged: from the dust and from the Tertiary upslope gypsiferous lutite outcrops. The source of gypsum in the Batea sequence is probably that of the central Ebro Valley, as in Alcañiz-Belchite, Quinto, the Bujaraloz-Pina areas and playa-lakes of Saladas de Monegros -where currently inactive yardang erosion morphologies have been described on gypsum (Gutiérrez-Elorza *et al*., 2002). Likewise, the source of gypsum in the Almenara sequence would be the gypsum found in the coalescent alluvial fan systems of the Ondara and Corb Rivers. Complete absence in the profiles could indicate no, or very little gypsum in the original dust. Interestingly, there is highly exchangeable Mg in some sequences (Almenara, Batea and Guiamets, DARP, 1987), and this could also indicate a dust source from saline playa-lake plains (Pueyo and Inglés, 1987).

2.5.2. Paleoenvironment, climatic evolution, ages and soil cover

The loess areas described in the Iberian Peninsula have always been described in climatic regions with low precipitation (< 400 mm/y, i.e. García-Giménez and González, 2010), as is the case in the proposed source area of Ebro valley today with between 250-400 mm/y. During the coldest phases of Quaternary glaciations these values were even lower, corresponding to a sparse shrub vegetation with very low cover (González-Sampériz *et al*., 2005) and most likely an unstable soil surface.

In our case at least three diferent generations of loess have been identified: a widespread one (OSL data ages between 18-34 ky) represented by Guiamets, Batea, Almenara and Tivissa (upper) sequences, an intermediate (no OSL dating available) represented by Tivissa lower sequence and an older one (minimum 115 ky according to OSL dates) represented by the Mas de l'Alerany (lower) sequence. The widespread loess deposits exhibit a weak soil development (Bw horizons; in some cases Bwk with stage I of calcium carbonate accumulation (Gile *et al*., 1966, Birkeland,1999) at best; By horizons in other cases). Very few sequences display weak Ab horizons, and are very weakly developed, pointing to a rapid rate of deposition and a lack of conditions for pedogenesis. The available pollen analysis in the Guiamets profile, sampled every 20 cm, show a very low presence of plant species in most levels, mainly represented by *Artemisia* sp. These results agree with the paleoenvironmental interpretation of the scarce/lack of vegetation cover in the vicinity of the studied area during the time of loess deposition, consisting of an open steppe vegetation under an arid climate (Riera, personal communication).The most recent sequences have been dated from 17ky BP (Batea) to 34 ky BP (Almenara).

These data are in good agreement with the information presented by Lewis *et al*. (2009) for the Cinca River, one of the few studies in the area with absolute dating (OSL) of terraces and related soils. The degree of soil development found by these authors for the above mentioned period (18-34 ky BP) is fairly similar to that of our loess deposits (type of B horizons; stage I of carbonate accumulation). The considerable soil development found by them in some of their profiles may be explained by the gravelly nature of the materials. Badia *et al*. (2009) found similar degrees of soil development on the lower Segre River (Ebro tributary) terraces. Our results also fit well with the loess dated to 20 ky BP by Lewis *et al*. (2009) in the Easthern Ebro Valley. Courty and Vallverdú (2001) suggest a generalized regional aeolian (loess) activity in their study of Abric Romaní, east from our study area, and tentatively date the dominant aeolian input to 39 ky BP, which points to an earlier eolian activty.

With two OSL ages in the Guiamets sequence, it was possible to determine the average rate of deposition as 18 ± 9 cm ky^{-1}, similar to the rate for the Matmata loess (Tunis, 7-10 cm ky^{-1} , Dearing *et al*., 2001).

The Last Glacial Maximum (LGM) in the Pyrenees is understood to have advanced earlier than in the rest of Europe, beginning as early as 50-60 ky and ending ~18 ky (Pallàs *et al*., 2006; Calvet *et al*., 2011). Our ages (18-34 ky) fit very well with the final phase of this cold episode (Fig. 11). The data is also in agreement with the fact that the vegetation for this cold and arid period was a steppe vegetation (*Artemisia* sp.) with low coverage (González-Sampériz *et al*., 2005).

The OSL age of the lower unit of Mas de l'Alerany, suggests a much older period of loess deposition, with a minimum age of 115 ky. Extensive soil development compared to that in the present climate (Btk; stage III of carbonation, rubefaction) in this sequence also indicates a very old age. The carbonate stage developments reported by Lewis *et al*. (2009) and Badia *et al*. (2009) in dated soils from the Cinca and Segre Rivers (Ebro North tributaries) correlate fairly well with this deposit. This degree of development of this sequence suggests soil formation during an interglacial period (Eemian), and therefore the loess would have to be deposited earlier, probably during the last episodes of the Riss glaciation. In any case, more data would be necessary to establish a regional trend with higher precision, which is difficult in the area due to the scarcity of such outcrops.

The lower Tivissa sequence exhibits an intermediate soil development between Guiamets and Mas de l'Alerany: a Bk horizon with stage III of calcium carbonate accumulation -with very large (more than 10 cm) calcium carbonate acumulations as rhizocretions. It appears in other sequences in the area, although they are much less extensive than the younger ones. The degree of carbonate stage development would correspond to an age range of approximately 100-180 ky according to the data of Lewis *et al*. (2009) for an area nearby, which appears to be almost contemporaneous with Mas de l'Alerany which exhibits a much more advanced development. Nevertheless, the formation of rhizocretions has been discussed by Klappa (1980), in the sense that they can form in relatively short periods of time. All information to date suggests that it could be considered an interstadial soil, but further work would be needed to establish the age of such deposits, although the presence of rhizocretions themselves makes sampling for OSL difficult. Iriondo and Khröling (2007) also mention the presence in the area of loess corresponding to the Younger Dryas.To date, we have not identified or dated such loess which could correspond to some small outcrops. They could be related to the ones described by García-Giménez and González (2010) as the youngest in the Tagus River, identified as Late Glacial/Holocene. We did not identify any more recent deposits in our area, besides the dated ones.

According to the established ages, we can confirm that our loess was transported and deposited during the coldest phases of the last glaciations (LGM at the end of Wurm and the end of Riss) and the soil development took place during interglacial warmer and moister periods (Eemian and Holocene), as suggested by Porter (2001) for the Chinese loess.

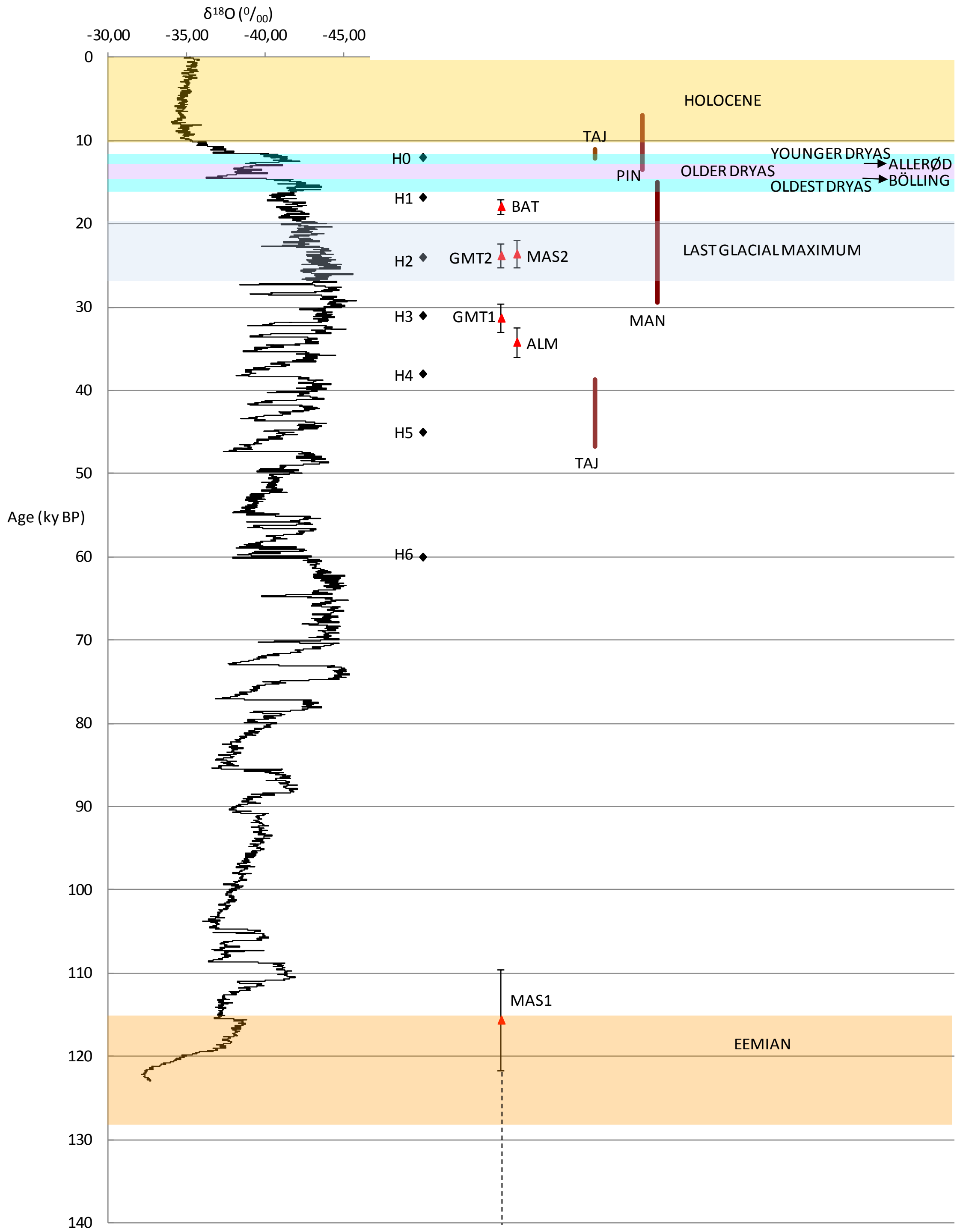

Figure 2.11. Chronology of the upper Pleistocene-Holocene of the studied samples. GRID data from North Greenland Ice Core Project members(2004). H0 to H6 indicate Heinrich events according to Hemming (2004). Identification of samples with red triangles are found in Table 2.2. Other ages for central Spain are MAN (Clayey dunes, La Mancha, Rendell *et al.*, 1994), PIN (Sand dunes, Tierra de Pinares, Bernat-Rebollal and Pérez-González 2008), and TAJ (Loess of Tagus River, García-Giménez and González-Martín, 2006)

2.6. Conclusions

In spite of the fact that loess has been reported in the NE Iberian Peninsula in the past, this work provides the first comprehensive study to ascertain the aeolian origin and characteristics of these materials. Soil cover and geomorphic processes in the Ebro basin were always interpreted with aeolian processes being considered of minor importance. The late recognition of large loess areas, a common feature in meridional Europe and North Africa (Cremaschi *et al*., 1990, Coudé-Gaussen 1982) now provides a better understanding of soils and geomorphology in the region.

The composition of the studied loess suggests a variety of sources which are fully compatible with the areas existing windward of the loess deposits. Due to their proximal origin, they are coarser than others described in the Western Mediterranean. They fit the conditions for a glacial loess according to Wright (2001) who stresses the general climatic conditions for its formation, more than the processes of silt making for the loess. In this sense, a multiplicity of processes for the reported loess production should be envisaged (glacial abrasion and arid -desert- related processes).

The majority of the deposits were formed between 17 and 34 ky, i.e. the cold phases of LGM. They show an incipient soil evolution compared with the surrounding soils. Nevertheless, in Tivissa the large rhizocretions may imply a more developed soil. The oldest deposits (Mas de l'Alerany lower sequence) are older than 115 ky (OSL), and possibly formed at the end of Riss; their pedogenic development is much greater than the rest, and could have occurred during the Eemian. Our loess ages are in good agreement with the environmental conditions of the coldest and most arid periods reported in literature for the Ebro Valley, with little or no vegetation and strong winds.

It is essential to broaden the extent of this research to neighbouring areas where loess has been identified, to fully understand the dynamics of material deposition during the Middle and Late Pleistocene. Future research will require the study of a larger number of primary loess sequences, in order to determine deposition rates more precisely, and to demonstrate the origin of the loess using, for example isotopic and, mineralogical markers, and/or by aerodynamic models using detailed digital elevation models.

Acknowledgements

We are grateful to Carmen Herrero, Carles Chico, Mario Carrillo and Josep Maria Llop (DAAM); Emili Ascaso (ICGC); Andreu Abellà, Montse Antúnez, Sílvia Porras and Asier Santana (U. of Lleida) for their

tireless support and help in the field, and for the laboratory analyses, figure designs and sample preparations.

References

Abellà A. 2011. Extensió i caracterització del material tipus loess a la zona de la Vall de l'Ebre. Treball Pràctic Tutorat ETSEA – Universitat de Lleida, Catalonia.

Adamiec G, Aitken M 1998. Dose-rate conversion factors: update. Ancient TL **16**: 37-50.

Artieda O. 2013. Morphology and micro-fabrics of weathering features on gyprock exposures in a semiarid environment (Ebro Tertiary Basin, Ne Spain). *Geomorphology* **196**: 198–210.

Badía D, Martí C, Palacio E, Sancho C, Poch RM. 2009. Soil evolution over the Quaternary period in a semiarid climate (Segre River terraces, northeast Spain). *Catena* **77**(3): 165-174.

Balasch JC, Herrero C, Castelltort X, Boixadera J. 2010. Loess peridesérticos en la cubeta de Móra d'Ebre (Depresión Prelitoral Catalana, NE España). *In:* Úbeda X, Vericat D, Batalla RJ. (Eds.), Avances de la Geomorfología en España 2008-2010. XI Reunión Nacional de Geomorfología, Solsona, pp. 349-352.

Balasch JC, Abellà A, Herrero C, Castelltort X, Poch RM, Bosch AD, Boixadera J. 2011. Suelos sobre loess en el valle inferior del río Ebro. *In*: Alcañiz J.M. (Ed.), Itinerarios edáficos por Cataluña: el Priorato, la Cerdaña y el Penedès. Fieldtrip Guide of the 28th Meeting of the SECS, Monografies Tècniques IGC nº 2, Barcelona, pp. 100-123.

Bech J, Solé A. 1977. Datos micromorfológicos sobre la recarbonatación de los suelos rojos de la Sierra Litoral (Barcelona). *In:* Alberdi, M.T. (Ed.), Actas de la II reunión nacional del Grupo Español de Trabajo del Cuaternario: Jaca 15-20 septiembre 1975, Vol. 6. Madrid, pp. 19-31.

Benyarku CA, Stoops G. 2005. Guidelines for preparation of rock and soil thin sections and polished sections. Quaderns DMACS 33, Universitat de Lleida, Lleida.

Bernat Rebollal M, Pérez-González A. 2008. Inland aeolian deposits of the Iberian Peninsula: Sand dunes and clay dunes of the Duero Basin and the Manchega Plain. Palaeoclimatic considerations. *Geomorphology* **102**(2): 207-220.

Birkeland PW. 1999. Soils and geomorphology. Oxford University Press. New York.

Boixadera J, Herrero C, Danés R, Roca J. 1989. Cartografía de suelos semiáridos de regadío: Área regable de los Canales de Urgell (Lérida). XVI Reunión de la SECS. DMCS-UPC &SECS. Barcelona.

Boixadera J, Rosell JA. 1997. Estudi detallat (1:25.000) de sòls de la zona a transformar en regadiu pel canal Segarra Garrigues. REGSA. Barcelona.

Bornand M, Legros JP, Moinereau J. 1977. Carte pédologique de la France à 1/100 000. Feuille Privas. INRA.

Brunnacker K, Lozek V. 1969. Löss-Vorkommen in Südost-Spanien. *Zeitschrift für Geomorphologie* **13**: 297-316.

Brunnacker K. 1969. Affleurements de loess dans les regions nord-mediterrannéennes. Révue de Géographie *Physique et de Géologie Dynamique* (2), **XI**, (3): 325-334.

Brunnacker KARL. 1980. Young Pleistocene loess as an indicator for the climate in the Mediterranean area. *Palaeoecology of Africa* **12**: 99-113.

Calvet M, Delmas M, Gunnell Y, Braucher R, Bourlès D. 2011. Recent Advances in Research on Quaternary Glaciations in the Pyrenees. *In*: Ehlers J, Gibbard PL, Hughes PD. (Eds.), Quaternary Glaciations: Extent and Chronology. Developments in Quaternary Science. Vol. 15. Elsevier, Amsterdam, pp. 127-139.

Carrillo G, Llop JM, Herrero C, Sió J, Boixadera J. 1998. Mapa de sòls detallat (1/25.000) del Garrigues Sud: Bovera–La Granadella. DARP- Generalitat de Catalunya. Lleida.

Coudé-Gaussen G, Olive P, Rognon P. 1983. Datation de dépôts loessiques et variations climatiques à la bordure nord du Sahara algéro-tunisien. *Revue de Géologie Dynamique et Géographie Physique* **24**: 61-73.

Coudé-Gaussen G, Mosser C, Rognon P, Tourenq J. 1982. Une accumulation de loess du Pleistocene supérieur dans le Sud-Tunisien; la coupe de Techine. *Bulletin de la Société Géologique de France* **2**: 283-292.

Coudé-Gaussen G. 1987. The Perisaharian Loess : Sedimentological Characterization and Paleoclimatical Significance. *GeoJournal* **15**(2): 177-183.

Coudé-Gaussen G. 1990. The loess and loess-like deposits along the sides of the western Mediterranean sea : genetic and palaeoclimatic significance. *Quaternary International* **5**: 1-8.

Courty MA, Vallverdú J. 2001. The microstratigraphic record of abrupt climate changes in cave sediments of the Western Mediterranean. *Geoarchaeology* **16**(5): 467-499.

Cremaschi M, Fedoroff N, Guerreschi A, Huxtable J, Colombi N, Castelletti L, Maspero A. 1990. Sedimentary and pedological processes in the Upper Pleistocene loess of northern Italy. The Bagaggera sequence. *Quaternary International* **5**: 23-38.

Crouvi O, Amit R, Enzel Y, Porat N, Sandler A. 2008. Sand dunes as a major proximal dust source for late Pleistocene loess in the Negev Desert, Israel. Quaternary Research **70**: 275-282.

Crouvi O, Amit R, Porat N, Gillespie AR, McDonald EV, Enzel Y. 2009. Significance of primary hilltop loess in reconstructing dust chronology, accretion rates, and sources: An example from the Negev Desert, Israel. *Journal of Geophysical Research* **114**: F02017 1-16.

Crouvi O, Amit R, Enzel Y, Gillespie A. 2010. Active sand seas and the formation of desert loess. *Quaternary Science Reviews* **29**: 2087-2098.

Culver SJ, Bull PA, Cambell S, Shakesby RA, Whalley WB. 1983. Environmental discrimination based on quartz grain surface textures: a statistical investigation. *Sedimentology* **30**: 129-136.

DAR. 2010. Mapa de sols (1:25.000). Zona frutícola i citrícola de les Terres de l'Ebre. Unpublished report. Generalitat de Catalunya. Lleida.

DARP. 1987. Caracterización edafoclimática de la zona regable del embalse de Guiamets (Tarragona). Unpublished report. Generalitat de Catalunya. Lleida.

Danés R, Herrero C, Boixadera Llobet J. 1991. Cartografia detallada de sòls en àrees de regadiu de Catalunya. *Quaderns agraris* **14**: 17-32.

Dearing JA, Livingstone IP, Bateman MD, White K. 2001. Palaeoclimate records from OIS 8.0–5.4 recorded in loess–palaeosol sequences on the Matmata Plateau, southern Tunisia, based on mineral magnetism and new luminescence dating. *Quaternary International* **7**: 43-56.

Duller GAT. 2003. Distinguishing quartz and feldspar in single grain luminescence measurements. *Radiation Measurements* **37**(2): 161-165.

Dumas B. 1977. Le levant espagnol. La gènese du relief. PhD Thesis, Université Paris-Sorbonne. Val de Marne (Paris XII)- CNRS, Paris.

FAO. 1990. Guidelines for soil description. Soil Resources, Management and Conservation Service, 3rd ed. FAO, Rome.

Faraco C. 1975. Estudio del colapso de la estructura de los limos yesíferos. *Revista de Obras Públicas* **122** (3127): 775-790.

Fink J. 1969. Le progrès de l'étude du loess en Europe. Bullétin de l'Association Française pour l'Étude du Quaternarie (1969): 3-12.

Galbraith RF, Roberts RG, Laslett GM, Yoshida H, Olley JM. 1999. Optical dating of single grains of quartz from Jinmium rock shelter, northern Australia. Part I: experimental design and statistical models. *Archaeometry* **41**: 339-364.

Gallart F. 1981. Neógeno superior y Cuaternario del Penedès (Catalunya, España). *Acta Geologica Hispanica* **16**(3): 151-157.

Garcia-Giménez R, González-Martín JA. 2006. Los loess del Valle Medio del río Tajo (Villarrubia de Santiago-Yepes, España). *Boletín de la Real Sociedad Española de Historia Natural (Sección Geología)* **101**(1-4): 51-78.

García-Giménez R, González JA. 2010. Las acumulaciones loéssicas de la Submeseta Sur. *In:* Sanjaume E, Gracia FJ. (Eds.), Las dunas en España. Sociedad Española de Geomorfología, Madrid, pp. 541-561.

Garcia-Giménez R, Vigil de la Villa R, González-Martín JA. 2012. Characterization of loess in central Spain: a microstructural study. *Environment Earth Sciences* **65**: 2125-2137.

Gile LH, Peterson FF, Grossman RB. 1966. Morphological and genetic sequences of carbonate accumulation in desert soils. *Soil Science* **101**: 347-360.

González J A, Asensio I, Fernández A, García-Giménez R, González-Amuchástegui MJ, Guerrero L, Rubio V. 2000. Acumulaciones de origen eólico frío en el modelado de los paisajes de la Rama castellana del Sistema Ibérico y de la Submeseta Sur. *In*: Peña, J.L., Sánchez, M., Lozano, M. V. (Eds.), Procesos y Formas Periglaciares en la Montaña Mediterránea. Instituto de Estudios Turolenses, Teruel, pp. 149-160.

González-Sampériz P, Valero-Garcés BL, Carrión JS, Peña-Monné JL, García-Ruiz JM, Martí-Bono C. 2005. Glacial and Lateglacial vegetation in northeastern Spain: New data and a review. *Quaternary International* **140**: 4-20.

Günster N, Eck P, Skowronek A, Zöller L. 2001. Late Pleistocene loess and their paleosols in the Granada Basin, Southern Spain. *Quaternary International* **76**/**77**: 241-245.

Gutiérrez-Elorza M, Desir G, Gutiérrez-Santolalla F. 2002. Yardangs in the semiarid central sector of the Ebro Depression (NE Spain). *Geomorphology* **44**: 155-170.

Haase D, Fink J, Haase G, Ruske R, Pécsi M, Richter H, Altermann M, Jäger K. D. 2007. Loess in Europe –its spatial distribution based on a European Loess Map, scale 1:2,500,000. *Quaternary Science Reviews* **26**(9-10): 1301-1312.

Hemming SR. 2004. Heinrich events: Massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint". *Reviews of Geophysics* **42** (1). Bibcode:2004RvGeo..42.1005H. doi:10.1029/2003RG000128. Retrieved 2013-05-15.

Herrero J. 1991. Morfología y génesis de suelos sobre yesos. INITAA, Madrid.

Herrero C, Boixadera J, Danés R, Villar JM. 1993. Mapa de sòls de Catalunya 1:25,000. Bellvís360-1-2. DGPIA-ICC. Generalitat de Catalunya. Barcelona.

Herrero J, Porta J, Fedoroff N. 1992. Hypergypsic soil micromorphology and landscape relationships in Northeastern Spain. *Soil Science Society of America Journal* **56**(4): 1188-1194.

Herrero J, Porta J. 2000. The terminology and the concepts of gypsum-rich soils. *Geoderma* **96**(1): 47-61.

Herrero J, Artieda O, Hudnall WH. 2009. Gypsum, a tricky material. *Soil Science Society of America Journal* **73**(6): 1757-1763.

IGME-Instituto Geológico y Minero De España-Diputación Provincial de Barcelona. 1956. Mapa Geológico de España E. 1:50,000 Hoja n. 363 (Manresa). Madrid.

IGME-Instituto Geológico y Minero De España. 1981. Mapa Geológico de España E. 1:50,000. Hoja 471 (Mora de Ebro). Madrid.

Iriondo MH, Kröhling DM. 2004. Loess yesífero en el Cuaternario Superior de la cuenca del Ebro: características generales. *In:* Rubió S. (Ed.), Homenaje a Emiliano Aguirre. Geología y Paleoecología, Madrid, pp. 45-50.

Iriondo MH, Kröhling DM. 2007. Non-classical types of loess. *Sedimentary Geology* **202**: 352-368.

IUSS Working Group WRB. 2006. World reference base for soil resources 2006. 2nd edition. World Soil Resources Reports No. 103. FAO, Rome.

Josa R. 1985. Estudi cronoseqüencial de sòls sobre les terrasses de l'Anoia: entre el Bedorc i Gelida. PhD Thesis. Universitat de Barcelona. Facultat de Geologia. Barcelona.

Klappa CF. 1980. Rhizoliths in terrestrial carbonates: classification, recognition, genesis and significance. *Sedimentology* **27**(6): 613-629.

Krinsley DH, Doornkamp JC. 1973. Atlas of quartz sand surface textures. Cambridge University Press. UK.

Lewis CJ, McDonald EV, Sancho C, Peña JL, Rhodes EJ. 2009. Climatic implications of correlated Upper Pleistocene glacial and fluvial deposits on the Cinca and Gállego Rivers (NE Spain) based on OSL dating and soil stratigraphy. *Global and Planetary Change* **67**(3): 141-152.

López-Martín F, Cabera M, Cuadrat JM. 2007. Atlas Climático de Aragón. Departamento de Medio Ambiente, Gobierno de Aragón, Zaragoza.

Lowick SE, Preusser F. 2011. Investigating age underestimation in the high dose region of optically stimulated luminescence using fine grain quartz. *Quaternary Geochronology* **6**(1): 33-41.

Maldonado A, Riba O, Orche E, Colombo F, Porta J. de Civis, J. 1979. Mapa Geológico de España. E 1:50.000. Hoja n 522 (Tortosa) 2ª serie. Madrid.

Margarit J, Monner A. 1996. Mapa de sòls (1:50.000) de la Terra Alta. INARSA, Barcelona.

Mejdahl V. 1987. Internal radioactivity in quartz and feldspar grains. *Ancient TL* **5**: 10–17.

Mensua S, Ibáñez MJ. 1975. Alvéolos en la depresión del Ebro. *Cuadernos de Investigación Geográfica* **2**: 3-14.

Mestdagh H, Haesaerts P, Dodonov A, Hus J. 1999. Pedosedimentary and climatic reconstruction of the last interglacial and early glacial loess–paleosolsequence in SouthTadzhikistan. *Catena* **35**: 197–218.

Mücher H, Sevink J, Bergkamp G, Jongejans J. 1990. A pedological and micromorphological study on Mediterranean loessial deposits near Gerona, NE-Spain. *Quaternary International* **5**: 9-22.

Murray AS, Wintle AG. 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiation Measurements* **37**: 377-381.

Muhs DR, McGeehin JP, Beann J, Fisher E. 2004. Holocene loess deposition and soil formation as competing processes, Matanuska Valley, southern Alaska. *Quaternary Reseach* **61**: 265-276.

Ninyerola M, Pons X, Roure JM. 2005. Atlas Climático Digital de la Península Ibérica. Metodología y aplicaciones en bioclimatología y geobotánica. Universitat Autònoma de Barcelona, Bellaterra, Catalonia.

North Greenland Ice Core Project members. 2004. North Greenland Ice Core Project Oxygen Isotope Data. IGBP PAGES/World Data Center for Paleoclimatology. Data Contribution Series # 2004-059. NOAA/NGDC Paleoclimatology Program, Boulder CO, USA.

Obruchev VA. 1945. Loess types and their origin. *American Journal of Science* **243**: 256-262.

Pallàs R, Rodés Á, Braucher R, Carcaillet J, Ortuño M, Bordonau J, Bourlés D, Vilaplana JM, Masana E, Santanach P. 2006. Late Pleistocene and Holocene glaciation in the Pyrenees: a critical review and new evidence from ^{10}Be exposure ages, south-central Pyrenees. *Quaternary Science Reviews* **25**(21): 2937-2963.

Pecsi M. 1990. Loess is not just accumulation of airborne dust. *Quaternary International* **7**/**8**: 1-21.

Poch RM. 1992. Fabric and physical properties of gypsic and hypergypsic horizons of the Ebro valley. PhD thesis. Universiteit Gent. Belgium.

Poch RM, Artieda O, Herrero J, Lebedeva-Verba M. 2010. Gypsic features. *In*: Stoops, G., Marcelino, V. and Mees, F. (Eds.), Interpretation of Micromorphological Features of Soils and Regoliths. Elsevier, Amsterdam. pp. 195-216.

Porta J, López-Acevedo M, Rodríguez R. 1986. Técnicas y experimentos en edafología. Col·legi Oficial d’Enginyers Agrònoms de Catalunya, Barcelona.

Porter SC. 2001. Chinese loess record of monsoon climate during the last glacial–interglacial cycle. *Earth-Science Reviews* **54**(1): 115-128.

Prescott JR, Hutton JT. 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long-term time variations. *Radiation Measurements* **23**: 497-500.

Preusser F, Kasper HU. 2001. Comparison of dose rate determination using high-resolution gamma spectrometry and inductively coupled plasma-mass spectrometry. **Ancient TL 19**: 17-21.

Pueyo JJ, Inglés M. 1987. Magnesite formation in recent playa lakes, Los Monegros, Spain. Geological Society, London, *Special Publications* **36**(1): 119-122.

Pye K. 1995. The nature, origin and accumulation of loess. *Quaternary Science Reviews* **14**: 653-667.

Rendell HM, Calderon T, Pérez-González A, Gallardo J, Millán A, Townsend PD. 1994. Thermoluminescence and optically stimulated luminescence dating of Spanish dunes. *Quaternary Science Reviews* **13**(5): 429-432.

Simonson RW, Hutton CE. 1954. Distribution curves for loess. *American Journal of Science* **252**: 99-105.

Smalley IJ, Vita-Finzi C. 1968. The formation of fine particles in sandy deserts and the nature of desert loess. *Journal of Sedimentary Petrology* **38**: 766-774.

Solé-Benet A, Julià R, Ballbé E. 1988. Micromorfología y mineralogía de un paleosuelo pleistoceno del Pla de Barcelona. *Acta Geologica Hispanica* **23** (3): 197-207.

Solé Sabarís L, Porta J, Solé N, Cuerda J, Muntaner A, Colom G. 1957. Livret guide de l'excursion L: Levant et Majorque, 5ème Congrès International INQUA, Madrid-Barcelona.

Stoops G. 1987. Soil Mineralogy. Part II: Techniques. Lecture Notes. ITC for Post-Graduated Soil Scientist - Universiteit Gent, Belgium.

Stoops G. 2003. Guidelines for analysis and description of soil and regolith thin sections. Soil Science Society of America Inc.

Torras A, Riba O. 1968. Contribución al estudio de los limos yesíferos del centro de la Depresión del Ebro. *Breviaria Geologica Asturica (Oviedo)* **11**: 125-137.

Van Zuidam RA. 1976. Geomorphological development of the Zaragoza region, Spain: processes and land forms related to climatic changes in a large Mediterranean River basin (No. 66). International Institute for the Aerial Survey and Earth Sciences (ITC).

Wintle AG, Murray AS. 2000. Quartz OSL: Effects of thermal treatment and their relevance to laboratory dating procedures. *Radiation Measurements* **32**: 387-400.

Wintle AG, Murray AS. 2006. A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. *Radiation Measurements* **41**: 369-391.

Wright JS. 2001. “Desert” loess versus “glacial” loess; quartz silt formation, source areas and sediment pathways in the formation of loess deposits. *Geomorphology* **36**: 231-256.

Yaalon DH. 1969. Origin of desert loess. *In* "Études sur le Quaternaire dans le Monde, Vol. 2." Bulletin de l'Association Francaise pour l'Etude du Quaternaire. Association Francaise pour l'Étude du Quaternaire (AFEQ), Paris, France. pp. 755.

Yaalon DH, Ganor E. 1973. The influence of dust on soils during the Quaternary. *Soil Science* **116**: 146-155.

Yaalon DH, Dan J. 1974. Accumulation and distribution of loess-derived deposits in the semi-desert and desert fringe areas of Israel. *Zeitschrift fur Geomorphologie Supplementband* **20**: 91-105.

Yaalon DH. 1987. Saharan dust and desert loess: effect on surrounding soils. *Journal of African Earth Sciences* **6**(4): 569-571.

Zander A, Degering D, Preusser F, Kasper H, U.Brückner H. 2007. Optically stimulated luminescence dating of sublittoral and intertidal sediments from Dubai, UAE: Radioactive disequilibria in the uranium decay series. *Quaternary Geochronology* **2**: 123-128.

CAPÍTOL 3:

Soil –landscape relationship in the lower parts of the Empordà basin (Catalonia, NE Iberian Peninsula)

Article submitted:

Boixadera, J., Antúnez, M., Poch, R.M. 201X. Soil –landscape relationships in the lower parts of the Empordà basin (Catalonia, NE Iberian Peninsula). *Spanish Journal of Soil Science*

SOIL – LANDSCAPE RELATIONSHIPS IN THE LOWER PARTS OF THE EMPORDÀ BASIN (CATALONIA, NE IBERIAN PENINSULA)

Jaume Boixadera[1,2*]; Monserrat Antúnez[2]; Rosa M. Poch[2]
[1]Dept. Agricultura, Ramaderia, Pesca, Alimentació i Medi Ambient, Generalitat de Catalunya.
[2]Dept. Medi Ambient i Ciències del Sòl, U. de Lleida.

[*]corresponding author: jaume.boix@macs.udl.cat

Abstract

Four benchmark soils developed in representative landforms of an area, previously mapped at detailed scale, in the Empordà Basin were selected to characterize important pedogenetic processes and to improve the soil mapping in the area and similar ones through developing a better understanding of the soil – landscape relationships. This basin is a relatively large region (1300 km^2) in northeastern Catalonia, where Neogene and Quaternary sediments outcrop. They are alluvial and delta fan deposits that mainly reflect a continental environment.

The soils studied show varying degrees of soil rubefaction and the main soil forming processes identified are: carbonate redistribution, clay illuviation, sodication, vertic features, abrupt textural changes and redoximorphic features. These processes, in the area, are expressed under different morphologies according mainly to parent material, landform and its age but also to human action and allow us to refine the conceptual soil-landscape model. Carbonate redistribution is a key process reflecting both changing general environmental conditions and also local chemical soil conditions

The present soil conditions and the soil forming processes investigated in the studied soils allow us to propose that eolian dust inputs in these soils have been low to moderate throughout, that the rainfall pattern in the last part of the Holocene was able to remove these dust inputs, but unable to leach carbonates from medium textured, moderately calcareous soils in the area when they are some kilometres from the sea and not directly affected by the dune system.

Key words: Mediterranean soils, genesis, mapping, clay illuviation, carbonate translocation, sodification, vertic features.

Supplementary material related to this article found, after references

3.1. Introduction

The nature and properties of the soil cover are the result of the interaction of the soil forming factors acting upon landforms modelled by geomorphological factors. The soil map is the representation of the soil cover (Hole and Campbell, 1985). The soil cover also provides us with a lot of information about (paleo) environmental features (climate and geomorphology among others).

Soil mapping is based on the so-called soil-landscape paradigm (Hudson, 1992). The quality of a soil map is strongly dependent (Western, 1979) on the model the soil surveyor uses to map the area. This model, in most cases is a conceptual one (Dijkerman, 1974): it is mentally constructed by the surveyor during the time of the mapping and it is one of the most widely used in pedology. The surveyor, when starting the survey uses his/her own knowledge and that acquired through his/her own experience and from reports, maps, scientific and technical papers to build up the preliminary soil-landscape model and then refines it during the survey.

The quality of the available soil-landscape model is key in order to have good mapping results of a certain area using either conventional soil mapping technics (Lagacherie *et al.,* 1995; Legros, 1996, DeBruin *et al.,* 1999) either digital soil mapping ones (McBratney *et al.,* 2003; Lagacherie, 2008) or even the modelling the formation soils (Samoüelian and Cornu, 2008) or landscape evolution (Minasny *et al.,* 2015).

Very often the knowledge of the soil forming processes is inadequate and additional work about soil genesis needs to be done during the survey. Usually new questions also arise during the survey. Altogether this means that there is a need to investigate the key soil forming processes present, because their expression through a set of soil properties allows the identification of the soil types in the field.

After the detailed (1/25,000) mapping (Boixadera *et al.,* 1990) of an area in the lower reaches of the Fluvià river (Empordà Basin), several questions arose about the morphology, soil formation and soil classification of several soils mapped .Four benchmark soils, in addition to other five ones showing relevant features, developed on representative landforms were selected to characterize important pedogenetic processes, through detailed chemical, mineralogical and micromorphological analyses, to improve soil mapping through developing a better understanding of the soil – landscape relationships.

In the Empordà Basin there are geomorphic surfaces with ages older as Pliocene. In these surfaces red (Mediterranean) soils have been developed. These type of soils have merited a lot of attention in the literature and its genesis have been reviewed recently by Fedoroff and Courty (2013). A significant part of the research reported in this paper is devoted to these type of soils.

3.2. Physical setting

The Empordà Basin is a relative large region (1300 km^2) in the northeastern Iberian peninsula, open to the sea at its eastern part. The basin is a relatively flat area bounded to the north by the Pyrenees, to the south by Les Gavarres (Hercinic), to the west and to the east by the Mediterranean Sea. The center of the basin is divided (Montgrí and Valldevià Mountains) into two parts: the southern one (*Baix Empordà*) – domains of the Ter and the Daró rivers - and the northern one (*Alt Empordà*) – domains of the Fluvià and the Muga rivers. The infilling of the Empordà Basin consists of the sedimentation of several Neogene and Quaternary alluvial and delta fans, deposited in a mainly continental environment. Some of these fans have grown as far as the coastline, favoring their transit and/or progradation over the sediments of marine and/or continental/marine transition (Montaner and Solà, 1998). The sub-recent alluvial plain entrenched between the older highlying rehens reliefs (Bach, 1987)

The altitude ranges from sea level up to 200 m. The climate is typically Mediterranean with annual rainfall about 600 mm and mean annual temperature of 15ºC. Both dry land and irrigated agriculture are the main land uses, beside some areas under natural vegetation.

From a morphological point of view, the Empordà Basin is formed by several glacis, mainly of detrital character, developed at the foot of the high-lying areas and later on affected by the drainage system (Serra *et al.,* 1994). Some volcanic materials appear, such as the Vilacolum outcrop, that consists of Miocene volcanic materials (trachyte) covered by Pliocene sediments (Martinell *et al.,* 2000).

The profiles studied were selected from an area Baix Fluvia of about 7,000 ha, located east of the Ventalló mountains, north of Vilademat and south of the Muga river, with the Mediterranean sea being the eastern boundary in the center of the basin (Fig. 3.1).

In the study area there are lower Pliocene deposits of Sant Climent delta fan outcrop (SGC-ICC, 1996), made of Paleozoic granites, metamorphic rocks and quartz from the northern Rodes Mountains (Picart *et al.,* 1996); the outcrops are located in the margin of the basin and paleoflows were in the direction of the center of the basin. Also, the Vilademat delta fan outcrops in the area

(SGC-ICC, 1995) as well as some deposits from the Sant Mori fan, made of metamorphic and quartzitic rocks (SGC-ICC, 1996).

The Pleistocene deposits in the study area are mainly the terrace system of Vilademat-Ventalló (IGME, 1983) but other authors identify, at a larger scale, a part with only calcareous rocks and Upper Pleistocene and Holocene fans covering it (SGC-ICC, 1995).

The lower parts of the basin, to the east, are Holocene and are occupied by a recent alluvial flood plain, made of fine-textured deposits. They show different degrees of salinity and drainage conditions depending on local topography and sedimentary environments. They include paludal areas reclaimed later on, locally named *closes*. In some other cases these areas are related to the prograding coastal dune system. The lagoon system is located in the lobes of the rivers and their reclamation started in the XV century, and as in the case of Estany de Sant Pere it was accomplished in the XIX century (Serra *et al.,* 1994). The sediments are silts and clays with some organic matter and salts due to their former connection with the sea.

Around 5000 years BP the sea level reached similar levels to the present (Riba, 1981) and the growth of the present Mediterranean deltas started. We should mention the fact that according to Montaner *et al.* (2014) the dynamics of the sea have been transgressive for at least 4000 years.

The deposits where Armentera soils have been developed are younger than 2,000 years BP according the studies carried out by Montaner *et al.* (2014) in the Empordà floodplain. The lagoon deposits, according the same authors, will be younger 157 years BP.

Finally, well-developed dune systems exist. Two different ones may be identified, the continental and the coastal (Marquès *et al.,* 2011). The first one is furnished by the alluvial plain and in the second the sand comes from the sea coast (Sainz Amor and Julià, 1999). The area has very favourable conditions for the development of such systems: the fluvial deposits and a strong NNE-N wind locally called *Tramontana*.

3.3. Materials and methods

The soils investigated were selected taking into account the main soil types existing in the area and the existing soil-landscape relationships (Table 3.1).These benchmark soils are developed into different geomorphic units with different parent materials (Table 3.2) and may be summarized as follows:

Soils of the older surfaces (Pliocene) (Aspres series and variants) (Table 3.3; Table S3.1-S3.2). The most extensive soils developed on the Pliocene terrestrial sediments belong to the Aspres series, a Typic Palexeralf. Other soils show either vertic features (Vertic Palexeralf), are acidic or, in some small depressions, have poor drainage. When developed in calcareous parent material they have a petrocalcic horizon (Aspres variant; Table S3.1-S3.2).

Soils of the Fluvià terraces and related surfaces (Pleistocene) (Ventalló series). The terraces of the Fluvià river and related surfaces are occupied by red soils which appear in some cases clearly buried by colluvial brown materials, close to the foot-slope of the Ventalló and Valldevià mountains. The larger part (Boixadera *et al.,* 1990) of the higher terraces has shallow soils with a petrocalcic horizon. They are mostly loamy Palexeralfs and Calcixerepts and a very few Rhodoxeralfs. The Palexeralfs merge gradually into the recent flood plain, as it occurs near Viladamat but also in the northern part of the area.

Soils of the (sub)recent (Holocene) alluvial fans (Armentera series). The Armentera series are very deep, calcareous, well drained soils, with an Ap-Bw-C horizon sequence, being classified as Typic Xerofluvents. Developed in the Fluvià alluvial plain, the soils are all irrigated.

Soils of the inter floodplain (Holocene) lobes (Closes variant). These soils are developed in the paludal sediments. The Closes series includes imperfectly drained soils with carbonate accumulations as nodules and other hard concretions at about 50 cm depth. They are located in depressions that used to be pastures surrounded by trees, a land use type locally named *closa* (from which the series name), but now also used for irrigated field crops. They are Sodic Calcixerepts.

Table 3.1. Soil distribution at the *Baix Fluvià* area (derived from Boixadera *et al.,* 1990)

Physiografic unit	**Soils (SSS, 2014) (+ main; - minor)**	**Typical horizon sequence**	**Main soils features*: clay features (Cl), rubefaction (RB), calcareous/non-calcareous (C/NC), redoximorphic (RX)**
Hills (Ventalló, Valldevià)	Typic Calcixerept (+)	Ap-Bk	RB,C
	Calcic Palexeralf (-)	A-Bt-Btk	Cl, RB, NC (40)/C
	Calcic Haploxeralf (-)	A-Bt-Btk	Cl, RB, NC (65)/C
	Petrocalcic Calcixerept (-)	Ap-Bkm	C
Pliocene surfaces	Typic Palexeralf (+)	A-Bt	Cl, RB, NC
	Petrocalcic Palexeralf (+)	A-Bt-Bkm	Cl, RB, NC (Bkm)/C
	Mollic Palexeralf (-)	A-Bt-Btg	Cl,NC
	Vertic Palexeralf (-)	A-Bt	Cl, NC, RX
	Calcic Palexeralf(-)	A-Bt-Btkc	Cl, RB, NC (95)/C
	Petrocalcic Calcixerept (-)	Ap-Bkm	RB, C
	Typic Calcixerept (-)	Ap-C-Ckc	C
Pleistocene terraces and related surfaces	Petrocalcic Palexeralf (+)	Ap-Bt-Bkm-Bkc	Cl, RB, NC (Bkm)/C
	Petrocalcic Calcexerept (+)	Ap-Bkm	RB, C
	Taphto-alfic Xerofluvent (-)	Ap-Bw-2Bt	Cl, RB, C
	Petrocalcic Rhodoxeralf (-)	Ap-Bt-Bkm	Cl, RB, C
Former in land lakes and depressions	Gypsic Haploxerept (+)	Ap-Bw-2Aby-2Bwy-2Bw	C
	Petrocalcic Calcixerept (-)	Ap-C-Bkm	C, RX
Holocene alluvial plain and delta	Typic Xerofluvent (+)	Ap-Bw-C	C
	Oxiaquic Xerofluvent (+)	Ap-Bw-C	C, RX
	Aquic Xerofluvent (+)	Ap-Bw-Bwg-C	C, RX
	Aquic Calcixerept (-)	Ap-Bw-Bwkc-C	C, RX
	Sodic Calcixerept (-)	Ap-Btkcna-Btna-C	Cl, C, RX

*RB: 5YR or redder; NC (xx): non calcareous up to this depth (cm); NC(Bkm): non calcareous up to this horizon

Table 3.2. Location, landform, geological units, parent materials and age of the geomorphic surface of the studied soils

Soils and profiles		Coordenades of the profile UTM (ED-56) X	Y	Altitude a.s.l (m)	Landform	Geological unit and parent material	Age of the geomorphic surface
Aspres soils	**E-43**	500750	4670780	45	Residual platform	Sant Mori alluvial system (NPMg). Very poorly sorted deposits with metamorphic and quartzite fragments	Pliocene (SGC-ICC, 1996)
	E-30	500780	4671300	35	Residual platform	Fluvial alluvial fans (NPFA). Lutites and poorly sorted deposits with limestone and granites	Pliocene (SGC-ICC, 1996)
	B8-9	503650	4672500	14	Residual platform	Sant Climent delta fan. Very poorly sorted quartzitic and schists deposits	Upper Pliocene > 2.5 My (SGC-ICC, 1996)
	E-22	504550	4670780	12	Residual platform	Sant Climent delta fan. Very poorly sorted quartzitic and schists deposits	Upper Pliocene > 2.5 My (SGC-ICC, 1996)
Ventallo soils	**B8-8**	502850	4665900	33	River terrace	Fluvial Quaternary alluvial fan. Alluvial and coluvial deposits; redish-brown clays and silty sands with gravel denses	Upper Pleistocene (30,000 Ky) (IGME, 1983) Pleistocene (SGC-ICC, 1995)
	E-135	503220	4665600	35	River terrace	Fluvial Quaternary alluvial fan. Alluvial and coluvial deposits; redish-brown clays and silty sands with gravel denses	Upper Pleistocene (30,000 Ky) (IGME, 1983) Pleistocene (SGC-ICC, 1995)
	E-122	502780	4662800	18	River terrace	Fluvial Quaternary alluvial fan. Alluvial and coluvial deposits; redish-brown clays and silty sands with gravel denses	Upper Pleistocene (30,000 Ky) (IGME, 1983) Pleistocene (SGC and ICC, 1995)
Armentera soils	**B8-10**	505120	4669200	6	Aluvial plain	Baix Fluvia alluvial fan. Silt with some sandy levels, light brown to grey	Holocene < 5Ky (Montaner et al., 2014)
Closes soils	**26CTP-80**	507107	4674804	-0.2	Drained lagoons	Baix Fluvia inter flood plain lobes. Grey-black clays and silty clays	Holocene < 1,500 Ky (Serra *et al.*, 1994)

This study uses information from Boixadera *et al.* (1990) and also from other surveys near by Carrillo *et al.* (1999); Margarit *et al.* (1993) all from the 1:25,000 Catalonia Soil Map, as well as from studies about soil-vegetation relationships (Porta *et al.,* 1994). Soil series in the Catalonia Soils maps were defined following the concept of Boulaine (1980) and SSS (1993). The criteria were parent material, drainage class, particle size distribution, genetic horizons, content of carbonates and soil classification according to Soil Taxonomy (Boixadera *et al.,* 1989 and DARP-ICC, 1993). The concept of "variant" was used following Soil Survey Manual (SSS, 1993).

The studied profiles (Table 3.2, Fig. 3.1) were described following the guidelines of SINEDARES (CBDSA, 1983). Samples were taken for physicochemical and mineralogical analyses. Undisturbed samples were collected at selected profiles and horizons for micromorphological analyses. The physicochemical analyses of the profiles were done according to MAPA (1993). Particle size distribution was determined by the pipette method, after organic matter removal with H_2O_2 and dispersion with Na-hexametaphosphate. Cation exchange capacity was determined by displacement with 1 M NH_4OAc (pH 7), and the exchangeable cations were measured by atomic absorption. Organic carbon, and total nitrogen were determined following Walkley-Black and Kjeldahl respectively. Soils are classified according to Soil Taxonomy (SSS, 2014) and Soil Taxonomy diagnostic horizons, and their terminology is used throughout the paper; classification according World Reference Base (IUSS, 2014) is given (Table 3.3) for correlation. Micromorphology was performed according to the procedures of Benyarku and Stoops (2005) for making vertical thin sections, 13 cm long and 5.5 cm wide, from air-dried undisturbed soil blocks. Stoops (2003) guidelines were followed for their description and study.

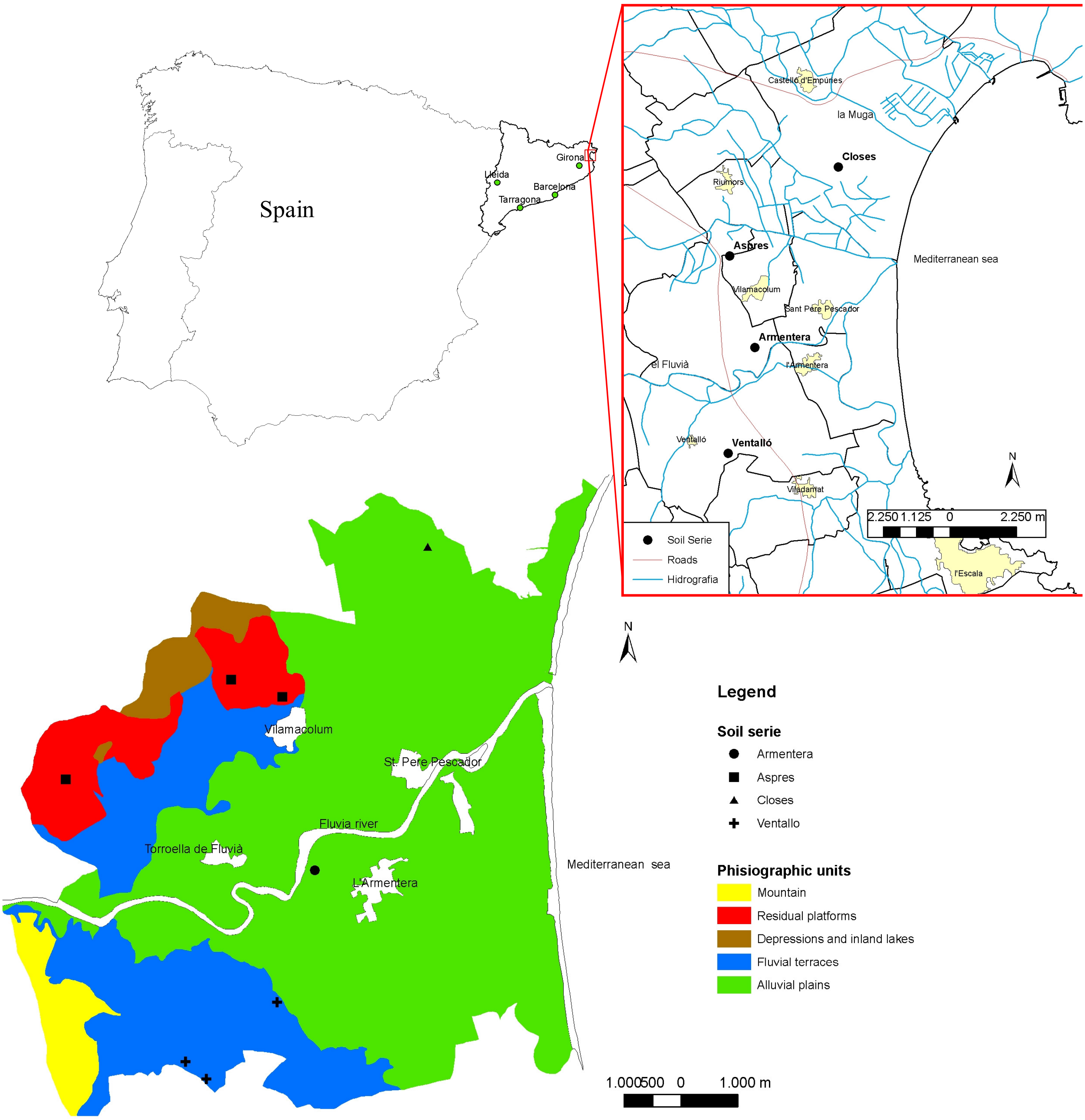

Figure 3.1. Physiografic units of the study area and situation of the studied profile

Total iron was determined after digestion by HCl and HNO_3. Dithionite soluble Fe was determined by the dithionite citrate buffered with sodium bicarbonate according to Mehra and Jackson (1960). Oxalate extractable Fe and Al were determined by extraction with acid ammonium oxalate 0.2M at pH 3 (Schwertman, 1964). In all extracts, Fe was determined by atomic absorption.

Semi-quantitative clay mineralogy was carried out through X-ray diffraction, using a Siemens D-500 difractometer. The clay samples were treated with acetic acid 0.5N to remove the carbonates and prepared as powder, oriented air-dry aggregates, and warmed at 500ºC during 3 hours.

The mineralogy of fine and coarse sand was done by separation of heavy and light minerals after elimination of carbonates and iron oxides (Stoops, 1987). Light minerals were stained using the method of Bailey and Stevens (1960), and minerals identified and counted under the petrographic microscope.

3.4. Results

3.4.1. Soil properties

In Tables 3.3, 3.4, 3.5, and 3.6 the main morphological, physicochemical and mineralogical characteristics of the studied of soils are shown.

Aspres series and variant. Some of the most prominent features of these soils, represented by profile B8-9, are the strong abrupt textural change from the coarser, whitish topsoil to the clayey subsoil. All the profiles have a large content of coarse elements: the whitish topsoil (up to 40-50 cm) contains only quartzitic rocks and the Bt horizon contains, in addition to that, weathered granites and schists in a clayey matrix. The weathering of granites is especially noticeable, with even the larger blocks down being disaggregated to sand and gravel particles. It has redoximorphic features down from 80 cm with chroma 1. Also it has slickensides from 55 cm (Btss).

The typical horizon sequence is A-Bt with or without textural discontinuities visible in the field (Table 3.3; Table S3.1-S3.2). The variant present Btss (B8-9) or in the case of soil developed in Pleocene surfaces with calcareous material a Bkm. The Bt horizon qualifies for argilic horizon. The base saturation is high and never qualifies as and Ultic subgroup.

Ventalló series. The Ventalló series has a central position in the wide range of soils of the terraces. The profile B8-8 is developed on the old terrace (Pleistocene) of the Fluvià river. It is a complex profile, only slightly calcareous at the surface, and with a petrocalcic horizon at depth. They are Petrocalcic Palexeralf.

The horizon sequence in the Ventalló soil A-2Bt-Bkm-Btkc with other soils showing calcium carbonate accumulation above the Bkn o below, making the clay illuvial horizon. The Bt horizon qualifies for an argilic horizon.

Armentera series. The profile B8-10 belongs to the Armentera series. It shows a clear fluventic character, and the youngness of the deposits is reflected by the charcoal fragments found at depth. They are classified as Typic Xerofluvent.

The horizon sequence is A-Bw-C. The Bw horizon does not qualifies for a cambic horizon.

Closes variant. Profile 26-CTP-80 belongs to a variant of the Closes series. It is the only salt-affected soil (Table 3.3). Besides redoximorphic features starting from 32 cm depth, it also presents sodic conditions (Table 3.9). They are classified as Sodic Calcixerept.

The horizon sequence is A-Btkcn-2Btn-3Btkcn. The Btn horizons do not qualify for a nitric or argilic horizon but the Btk horizon are nodules calcic horizons.

In all profiles, clay mineralogy (Table 3.7) is dominated in all cases by illite. There is a very significant amount of kaolinite in the *Aspres* soil. Smectite is present only in very low amounts in the same profile and is absent in the rest. Fleta and Escuer (1991) already mentioned the presence of smectite in the Pliocene parent materials.

The sand mineralogy of the Aspres and Ventalló series (Table 3.6) shows a predominance of quartz in the light fraction. The distribution in depth of heavy minerals, mostly of opaques and of minerals typical for metamorphic rocks in profile B8-9, confirms the lithological discontinuities observed in the field in this profile.

Table 3.3. Morphological characteristics of the studied soils

Soil , profile number and classification (SSS 2014; IUSS WRB, 2014)	Horizon	Depth (cm)	Sand	Silt	Clay	Texture[1] USDA	Colour (moist)	R.I[2]	Coarse fragments ϕ^3 > 2mm (volume %)	Soil structure	Main features
			---------	(%)	-------						
Aspres variant B8-9	Ap	0-22	43.7	36.9	16.4	L	10YR3/3	15	16-35	subangular blocky	coarse fragments: unweathered quartzites
Vertic Palexeralf	A_2	22-33	46.0	24.6	29.3	SCL	10YR5/3	9	>70	subangular blocky	coarse fragments: unweathered quartzites
Cutanic Luvisol	2Bt	33-55	21.0	8.5	70.4	C	7.5YR5/8	28	>70	blocky to prismatic, fine	frequent clay coatings, coarse fragments: unweathered quartzites
	3Btss	55-80	31.3	13.0	57.7	C	10YR6/8	20	16-35	blocky to prismatic, fine	frequent clay coatings, some slickensides and pressure faces, unweathered quartzites
	4Bt	80-230	53.4	15.0	31.5	SCL	10YR6/8	20	>70		frequent clay coatings, some slickensides and pressure faces; mottling (7.5 YR 7/1),frequent pisolites (Fe and Mn); very many coarse fragments highly weathered granites and schists, unweathered quartzites.
Aspres series E-22	Ap	0-35	61.5	22.2	15.2	SL	7.4YR3/4	23	5-15	moderate subangular blocky	unweathered quartzites. No mottles
Typic Plesxeralf	Bt_1	35-100	50.9	11.0	38.1	SC	2.5YR4/8	45	1-5	strong, subangular blocky	unweathered quartzites. No mottles. Common clay coatings
Cutanic Luvisol	Bt_2	100-150	60.7	6.5	31.9	SCL	2.5YR4/8	45	1-5	strong, subangular blocky	unweathered quartzites;highly weathered schists and granites. Common clay coatings. No mottles.
	Bt_3	150-175	59.9	12.3	27.8	SCL	2.5YR4/8	45	5-15	moderate, subangular blocky	Few unweathered quartzites. Common clay coatings. No mottles.
	Bt_4	175-215	67.5	10.7	21.8	SCL	2.5YR4/8	45	1-5	weak, subangular blocky	unweathered quartzites. Common clays coatings. No mottles.
	Bt_5	215-235	60.1	5.4	32.3	SCL	5YR6/8	27	16-35	moderate, subangular blocky	unweathered quartzites and highly weathered granites and schitst. Common clay coatings. No mottles.

[1]Texture USDA; L: loam; SCL: sandy clay loam; C: clay; SL: sandy loam; [2]R.I.: Redness Index= [(25-nhue)* chroma]/value. Modified from Hurst, 1977; nhue value: 10YR=10; 7.5YR=7.5; 5YR=5; 2.5YR=2.5; 10R=0; [3]ϕ: diameter.

Table 3.3. Morphological characteristics of the studied soils (cont.)

Soil , profile number and classification (SSS 2014; IUSS WRB, 2014)	Horizon	Depth (cm)	Sand	Silt	Clay	Texture[1] USDA	Colour (moist)	R.I[2]	Coarse fragments ϕ^3> 2mm (volume %)	Soil structure	Main features
			---------	(%)	-------						
Ventalló series B8-8 Petrocalcic Palexeralf Chromic-Hypercalcic-Luvisol (cutanic)	Ap	0-23	64.8	17.9	17.3	SL	7.5YR4/6	26	5-15	strong, granular, medium	coarse fragments; polygenic and petrocalcic fragments
	AB	23-52	64.8	17.6	17.7	SL	5YR3/6	40	5-15	weak, subangular blocky, medium	coarse fragments; unweathered polygenic
	2Bt	52-80/99	46.0	19.8	34.1	SCL	2.5YR4/6	34	5-15	strong, subangular blocky, medium	frequent clay coatings and clay bridges between grains; coarse fragments: unweathered subrounded-spheroidal poligenic
	2Bkcm	80/99-103/107	-	-	-	-	-	-	-	-	moderately cemented by carbonate, banded hard and soft nodules; coarse fragments in the petrocalcic horizon
	3Btkc$_1$	103/107-163	52.8	22.5	24.7	SCL	2.5YR5/8	36	1-5	moderate, subangular blocky	few clay coatings, very abundant carbonate nodules, coarse and very hard, soft powdery lime; coarse fragments: unweathered subrounded-spheroidal poligenic
	3Btkc$_2$	163-213	52.4	19.7	27.9	SCL	2.5YR5/6	27	1-5	weak, subangular blocky, medium	frequent clay coatings, frequent carbonate nodules, coarse and very hard, soft powdery lime; coarse fragments: unweathered subrounded-spheroidal poligenic
	4Btkc$_3$	213-269	54.2	22.8	23.0	SCL	5YR6/6	20	1-5	weak, subangular blocky, medium	frequent clay coatings and abundancy clay bridges, frequent $CaCO_3$ nodules, coarse and very hard, soft powdery lime; coarse fragments: unweathered subrounded-spheroidal poligenic

[1]Texture USDA; L: loam; SCL: sandy clay loam; C: clay; SL: sandy loam; [2]R.I.: Redness Index= [(25-nhue)* chroma]/value. Modified from Hurst, 1977; nhue value: 10YR=10; 7.5YR=7.5; 5YR=5; 2.5YR=2.5; 10R=0; [3]ϕ: diameter.

Table 3.3. Morphological characteristics of the studied soils (cont.)

Soil , profile number and classification (SSS 2014; IUSS WRB, 2014)	Horizon	Depth (cm)	Sand	Silt	Clay	Texture[1] USDA	Colour (moist)	R.I[2]	Coarse Fragments ϕ^3 > 2mm (volume %)	Soil structure	Main features
			----------- (%) ---------								
Ventalló series E-135 Petrocalcic Palexeralf Chromic-Hypercalcic-Luvisol (cutanic)	Ap	0-20	67.6	9.4	23.9	SCL	5YR4/6	30	1-5	subangular blocky, fine	coarse fragments: limestone
	$2Bt_1$	20-34	57.9	16.0	25.9	SCL	5YR4/6	30	1-5	subangular blocky, fine	coarse fragments: limestone. Clay cutans. No mottles
	$2Bt_1$	34-48	64.3	12.3	22.8	SCL	5YR4/6	30	1-5	subangular blocky, fine	coarse fragments: limestone. Clay cutans. No mottles
	$2Bt_2$	48-60	61.7	9.7	27.2	SCL	2.5YR4/6	34	1-5	subangular blocky, coarse	coarse fragments: limestone. Clay cutans. No mottles
	$2Bt_2$	60-72	58.9	11.9	29.8	SCL	2.5YR4/6	34	1-5	subangular blocky, coarse	coarse fragments: limestone. Clay cutans. No mottles
	2Btk	72-84	65.2	11.0	22.8	SCL	5YR4.5/6	27	36-70	structureless	coarse fragments: limestone. Few clay cutans. Carbonate coatings
	3Bkm	84-114	-	-							coarse fragments in the petrocalcic: quarzitc. Strongly cemented
	3Bkc	114-129	-	-			7.5YR6.5/8	22	5-15	structureless	coarse fragments: limestone anc quartzite. Calcium carbonate hard nodules
	3Bkm	129-144	-	-							strontly cemented petrocalcic

[1]Texture USDA; L: loam; SCL: sandy clay loam; C: clay; SL: sandy loam;[2]R.I.: Redness Index= [(25-nhue)* chroma]/value. Modified from Hurst, 1977; nhue value: 10YR=10; 7.5YR=7.5; 5YR=5; 2.5YR=2.5; 10R=0 [3]ϕ: diameter.

Table 3.3. Morphological characteristics of the studied soils (cont.)

Soil, profile number and classification (SSS 2014; IUSS WRB, 2014)	Horizon	Depth (cm)	Sand	Silt	Clay	Texture[1] USDA	Colour (moist)	R.I[2]	Coarse Fragments ϕ^3 > 2mm (volume %)	Soil structure	Main features
			--------- (%) -------								
Armentera series B8-10	Ap	0-27	37.7	46.6	15.7	L	10YR4/6	23	absent	-	-
Typic Xerofluvent Calcaric Fluvisol	Bw_1	27-72	32.6	51.4	16.0	SL	10YR4/6	23	absent	moderate, subangular blocky, medium	-
	Bw_2	72-123	28.8	54.7	16.5	SL	10YR4/6	23	absent	moderate, subangular blocky, medium	very few carbonate pseudomycelia
	Bw_3	123-167	33.2	50.7	16.1	SL	7.5YR4/4	18	absent	moderate, subangular blocky, medium	very few carbonate pseudomycelia
	Bw_4	167-212	27.5	52.5	20.0	SL	10YR4/6	23	absent	-	
Closes variant 26CTP-80	Ap_1	0-13	13.4	49.3	37.3	SCL	10YR4/3	11	absent	very weak, subangular blocky, medium	vertical cracks, 1 cm width
Sodic Calcixerepts Episidic Calcisol	Ap_2	13-32	15.9	45.0	39.1	SCL	10YR4/3	11	absent	weak, subangular blocky, medium	-
	Btkcn	32-82/96	24.0	42.4	33.6	CL	10YR5/4	12	absent	strong, prismatic, medium	frequent mottling, frequent soft and hard carbonate concretions, Fe and Mn concretions
	2Btn	82/96-96	50.8	28.3	20.9	L	10YR5/6	18	absent	very weak, subangular blocky	frequent coatings on ped faces, frequent mottling
	3Btkcn	96-130	79.3	9.6	11.1	SL	10YR5/6	18	absent	moderate, prismatic, coarse	frequent coatings on ped faces, frequent mottling, hard carbonate and Fe and Mn concretions

[1]Texture USDA; L: loam; SCL: sandy clay loam; C: clay; SL: sandy loam; [2]R.I.: Redness Index= [(25-nhue)* chroma]/value. Modified from Hurst, 1977; nhue value: 10YR=10; 7.5YR=7.5; 5YR=5; 2.5YR=2.5; 10R=0 [3]ϕ: diameter.

Table 3.4. Chemical characteristics of the studied profiles

Soil , profile number and classification (SSS 2014;IUSS WRB, 2014)	Horizons	pH[1] H_2O 1:2.5	EC[2] 1:5 (dS/m, 25ºC)	$CaCO_3$[3] eq. (%)	OC[4] (%)	CEC[5] (cmol(+)/ kg)	V[6] (%)	Exchangeable cations (cmol(+)/kg)			
								Ca^{2+}	Mg^{2+}	Na^+	K^+
Aspres B8-9	Ap	6.1	0.19	-	2.3	12.3	100	9.7	1.2	0.2	1.2
	A_2	6.3	0.11	-	0.6	13.6	88	9.6	1.5	0.2	0.7
	2Bt	6.9	0.11	-	-	23.1	100	18.3	3.8	0.3	0.7
	3Btss	7.5	0.14	-	-	21.2	100	17.0	3.5	0.3	0.4
	4Bt	7.5	0.16	-	-	14.9	100	11.3	3.2	0.2	0.2
Aspres E22	Ap	7.1	0.15	-	2.7	11.2	100	8.0	2.1	0.0	1.1
	Bt_1	6.0	0.14	-	-	14.8	100	12.2	2.2	0.1	0.3
	Bt_2	7.4	0.49	-	-	10.6	100	8.8	1.6	0.1	0.2
	Bt_3	7.1	0.10	23.6	-	11.0	100	8.9	1.9	0.1	0.1
	Bt_4	6.9	0.08	29.1	-	7.2	100	5.6	1.4	0.0	0.1
	Bt_5	7.0	0.10	6.2	-	12.8	100	10.7	1.9	0.1	0.2
Ventalló E-135	Ap	8.5	0.14	3.5	0.5	-	-	-	-	-	-
	$2Bt_1$	8.5	0.14	1.0	-	-	-	-	-	-	-
	$2Bt^1$	8.2	0.16	0.5	-	-	-	-	-	-	-
	$2Bt^2$	8.1	0.10	0.5	-	-	-	-	-	-	-
	$2Bt_2$	8.2	0.20	0.5	-	-	-	-	-	-	-
	$2Btk_3$	8.5	0.90	10.0	-	-	-	-	-	-	-
	3Bkc	8.3	0.40	19.6	-	-	-	-	-	-	-
Ventalló B8-8	Ap	8.1	0.15	6.5	1.4	9.3	100	8.4	0.5	0.1	0.3
	AB	8.1	0.13	6.5	0.5	8.1	100	7.4	0.4	0.1	0.3
	2Bt	8.0	0.12	1.5	0.3	13.6	100	12.5	0.8	0.1	0.3
	2Bkcm	-	-	57.2	-	-	-	-	-	-	-
	$3Btkc_1$	8.5	0.11	23.6	-	10.8	100	9.5	0.7	0.4	0.2
	$3Btkc_2$	8.4	0.11	29.1	-	10.3	100	9.3	0.6	0.2	0.2
	$4Btkc_3$	8.4	0.12	6.2	-	10.9	100	9.8	0.6	0.2	0.2

[1]pH: relation 1soil: 2.5distilled water; [2] EC: electrical conductivity relation 1soil:5distilled water at 25ºC; [3]$CaCO_3$[3]eq: calcium carbonate equivalent; [4]OC: organic carbon; [5]CEC: cation exchange capacity; [6]V: base saturation.

Table 3.4. Chemical characteristics of the studied profiles (cont.)

Soil , profile number and classification (SSS 2014;IUSS WRB, 2014)	Horizons	pH[1] H_2O 1:2.5	EC[2] 1:5 (dS/m, 25ºC)	$CaCO_3$[3] eq. (%)	OC[4] (%)	CEC[5] (cmol(+)/ kg)	V[6] (%)	Exchangeable cations (cmol(+)/kg)			
								Ca^{2+}	Mg^{2+}	Na^+	K^+
Armentera B8-10	Ap	8.1	0.16	30.8	1.2	8.5	-	-	0.9	-	-
	Bw_1	8.3	0.13	21.6	0.3	6.1	-	-	0.9	-	-
	Bw_2	8.3	0.13	31.3	0.2	6.0	-	-	1.1	-	-
	Bw_3	8.2	0.26	27.2	0.2	6.1	-	-	2.1	-	-
	Bw_4	8.2	0.27	27.1	0.3	6.2	-	-	2.7	-	-
Closes variant 26CTP-80	Ap_1	8.9	0.89	21.0	2.1	14.2	-	-	-	-	-
	Ap_2	9.4	1.20	19.9	1.7	14.1	-	-	-	-	-
	Btkcn (32-64)	9.6	0.77	19.1	0.3	9.3	-	-	-	-	-
	Btkcn (64-96)	9.6	0.74	19.2	0.2	9.1	-	-	-	-	-
	2Btn	9.5	0.85	19.9	0.3	9.6	-	-	-	-	-
	3Btknc	9.5	0.86	19.8	0.3	14.1	-	-	-	-	-

[1]pH: relation 1soil: 2.5distilled water; [2] EC: electrical conductivity relation 1soil:5distilled water at 25ºC; [3]$CaCO_3$[3]eq: calcium carbonate equivalent; [4]OC: organic carbon; [5]CEC: cation exchange capacity; [6]V: base saturation.

Table 3.5. Carbonate-free particle size distribution of profiles B8-9 (Aspres) and B8-8 (Ventalló)

Profile	Horizon	Sand (ϕ[1], mm)						Silt (ϕ, mm)		
		2.00 1.00	1.00 0.50	0.50 0.25	0.25 0.10	0.10 0.05	Total 2.00 0.05	0.05 0.02	0.020 0.002	Total 0.050 0.002
Aspres B8-9	Ap	4.5	9.2	11.0	12.4	17.1	54.2	22.7	23.1	45.8
	A_2	18.6	13.6	10.2	13.2	13.2	65.2	15.0	19.8	34.8
	2Bt	13.9	13.2	13.2	15.6	15.6	71.2	15.6	13.2	28.8
	3Btss	12.4	15.1	15.6	12.2	12.2	70.7	14.4	14.9	29.3
	4Bt	0.6	23.2	16.2	10.2	10.2	78.1	11.3	10.7	21.9
Ventalló B8-8	Ap_1	31.9		48.3			80.1	10.9	9.0	19.9
	AB	31.5		50.1			81.6	8.7	9.7	18.4
	2Bt	25.5		46.5			71.9	12.6	15.5	28.1
	2Bknm									
	$3Btkn_1$	22.5		44.4			67.0	14.0	19.0	33.0
	$3Btkn_2$	19.8		44.5			64.2	14.9	20.9	35.8
	$4Btkn_3$	23.3		42.6			65.9	14.5	19.6	34.1

[1]ϕ: diameter

Table 3.6. Sand mineralogy: profiles B8-9 (Aspres) and B8-8 (Ventalló)

Heavy and light minerals[1]	Profiles and horizons								
	Profile B8-9 (Aspres)			Profile B8-8 (Ventalló)					
	Ap_1	2Bt	3Btss	Ap_1	AB	2Bt	$3Btkc_1$	$3Btkc_2$	$4Btkc_3$
Heavy minerals in fine sand									
Opaques	32	14	19	26	26	28	39	ne[2]	ne
Zircon		1			4		2	ne	ne
Rutile	2	1	1					ne	ne
Kyanite	2	3	1	4	2	2		ne	ne
Sillimanite		2	3	2	1			ne	ne
Andalusite	5	3	5	3	1	3		ne	ne
Staurolite		1	1		1		1	ne	ne
Garnet	2	3	4	1		1	1	ne	ne
Hornblende		11	3	1	2	2	1	ne	ne
Augite		1	1		1	1		ne	ne
Epidote	2	2		1	2	1		ne	ne
Diopside				2	5			ne	ne
Hyperstene	2					1		ne	ne
Chlorite		1	5					ne	ne
Rock fragments	1	4	4	4	1	1		ne	ne
Alterites	2	3	3	6	4	10	6	ne	ne
Light minerals in fine sand									
Quartz	56	80	58	57	56	69	55	56	60
K-feldspars	17	12	6	11	13	14	12	9	16
Ca-feldspars	27	8	36	32	31	17	33	35	24
Light minerals in coarse sand									
Quartz	56	39	35	41	42	44	30	46	40
K-feldspars	10	8	9	5	13	8	6	2	8
Ca-feldspars	9	12	12	28	27	28	32	24	30
Rock fragments (mainly quartzite)	25	41	44	26	18	20	32	28	22

[1]Heavy and light minerals are counted over 50 and 100 grains respectively; [2] n.e: not enough grains for heavy mineral counting

Table 3.7 displays the different content of extractable iron oxides. Bt horizons have higher ratios of free iron (Fe dithionite) than Bw ones. Also, crystalline iron is much higher in Bt than in Bw horizons. When interpreting these data we have to consider the different initial mineralogy. The free iron, extracted with sodium dithionite, is much higher in the Bt horizons of older soils. Crystalline iron (Fe_{dt} – Fe_{ox}) is also much higher in these soils, with amorphous iron (Fe_{ox}) being higher in topsoils, younger soils and poorly drained soils. The ratio of crystalline iron/total iron is also much higher in older than younger soils, while Fe_{dt}/clay is higher in red soils. The ratio amorphous iron/total iron is much higher in younger soils (B horizons) than old ones. The so-called *weathering index* (Fedt / Fet) is 50% higher in older than younger soils and in the older, higher in the Bt horizon.

3.4.2. Micromorphology

Aspres series (B8-9). The Aspres soil is non calcareous, which is shown in thin section in specific b-fabrics: stipple–speckled at the surface to progressively mosaic- and striated fabrics as clay content increases, reaching cross-striated fabrics (expression of slickensides described in the field) in depth. These features indicate a micromass made of clays with some shrinking-swelling properties. The lithologic discontinuities observed in the field are expressed as different c/f ratios (proportion coarse/fine material) depending on the horizon. Coarse mineral grains are highly weathered, mainly in the deepest horizons, as is shown in the plagioclases and schist fragments, which show a strong pedoplasmation (Fig. 3.2a); in the surface horizon such coarse mineral grains are absent.

Clay illuviation is very well expressed in the most gravelly/sandy horizons, as coatings of grains and infillings of packing pores. The coatings are made of microlaminated clay, but with a moderate degree of deformation, due to the nature of the clays and also to the age of the soil (Fig. 3.2a).

In-situ (orthic) nodules of Fe-oxihydroxides are found deeper than 33 cm on, with no relation to the present-day pore system, which means that the Fe mobilization is probably a paleofeature formed during wetter periods, contemporary with the clay illuviation.

Aspres soils in the well drained profiles present similar colours. However profile B8-9, a somewhat poorly drained Aspres variant, has not such a red colour.

The Bt horizons of profile E-30 (Table S3.1) are made of quartzitic gravels and coarse sand, and a decarbonated micromass made of clay, fine silt and iron oxides. The c/f related distribution is mainly chitonic and close porphyric in some spots, with packing pores as main voids. In the latter, the b-fabric is mosaic-speckled and striated, which points to swelling clays as possible components of the micromass. Microlaminated clay coatings are ubiquitous around the coarse fragments. Some of them are deformed and mixed with the striated micromass. Another pedofeature is the presence of few typic nodules of Fe-oxihydroxides.

Ventalló series (B8-8). The Ventalló soil is a complex, polycyclic soil, that has undergone several additions of calcareous and siliceous materials during its formation, together with carbonation / decarbonation processes and clay illuviation.

Table 3.7. Oxalate extractable aluminium, total iron and forms of iron of the soils

Profile	Horizon	Depth (cm)	Soil colour (matrix moist)	R.I[1]	Clay[2] (%)	Fe_t[3] (%)	Fe_{dt}[4] (%)	Fe_{ox}[5] (%)	Fe_{dt}/Fe_t	Fe_{ox}/Fe_t	Fe_{ox}/Fe_{dt}	$Fe_{dt}-Fe_{ox}$	Fe_t-Fe_{dt}	$(Fe_{dt}-Fe_{ox})/Fe_t$	Fe_{dt}/Clay	Fe_t/Clay
Aspres B8-9	Ap	0-22	10YR3/3	15	16.4	1.77	1.01	0.13	0.57	0.07	0.13	0.88	0.76	0.50	0.06	0.11
	A_2	22-33	10YR5/3	9	29.3	2.97	1.82	0.13	0.61	0.04	0.07	1.69	1.15	0.57	0.06	0.10
	2Bt	33-55	7.5YR5/8	18	70.4	5.20	3.77	0.07	0.73	0.01	0.02	3.70	1.43	0.71	0.05	0.07
	3Btss	55-80	10YR /8	15	57.7	4.66	2.99	0.07	0.64	0.02	0.02	2.92	1.67	0.63	0.05	0.08
Aspres E-22	Ap	0-35	7.4YR3/4	23	15.2	1.32	0.72	0.06	0.55	0.05	0.08	0.66	0.60	0.50	0.05	0.09
	Bt_1	35-100	2.5YR4/8	45	38.1	2.77	1.64	0.05	0.59	0.02	0.03	1.59	1.13	0.57	0.04	0.07
	Bt_2	100-150	2.5YR4/8	45	31.9	2.22	1.46	0.05	0.66	0.02	0.03	1.41	0.76	0.64	0.05	0.07
	Bt_3	150-175	2.5YR4/8	45	27.8	2.04	1.33	0.04	0.65	0.02	0.03	1.29	0.71	0.63	0.05	0.07
	Bt_4	175-215	2.5YR4/8	45	21.8	1.80	0.91	0.03	0.51	0.02	0.03	0.88	0.89	0.49	0.04	0.08
	Bt_5	215-235	5YR6/8	27	32.3	2.73	1.44	0.05	0.53	0.02	0.03	1.39	1.29	0.51	0.04	0.08
Ventalló B8-8	Ap_1	0-23	7.5YR4/6	26	14.0	2.05	0.98	0.03	0.48	0.01	0.03	0.95	1.07	0.46	0.07	0.15
	AB	23-52	5YR3/6	40	14.8	2.05	1.16	0.05	0.57	0.02	0.04	1.11	0.89	0.54	0.08	0.14
	2Bt	52-80	2.5YR4/6	34	34.8	3.53	2.08	0.08	0.59	0.02	0.04	2.00	1.45	0.57	0.06	0.10
	$3Btkc_1$	107-163	2.5YR5/8	36	35.2	2.50	1.51	0.02	0.60	0.01	0.01	1.49	0.99	0.60	0.04	0.07
	$3Btkc_2$	163-213	2.5YR5/6	27	36.8	2.37	1.56	0.03	0.66	0.01	0.02	1.53	0.81	0.65	0.04	0.06
	$4Btkc_3$	213->269	5YR6/6	20	29.1	2.70	1.83	0.05	0.68	0.02	0.03	1.78	0.87	0.66	0.05	0.09
Armentera B8-10	Ap	0-27	10YR4/6	23	15.7	2.11	0.88	0.10	0.42	0.05	0.11	0.78	1.23	0.37	0.06	0.13
	Bw_1	27-72	10YR4/6	23	16.0	2.53	1.33	0.10	0.53	0.04	0.08	1.23	1.20	0.49	0.08	0.16
	Bw_2	72-123	10YR4/6	23	16.5	2.69	1.40	0.11	0.52	0.04	0.08	1.29	1.29	0.48	0.08	0.16
	Bw_3	123-167	10YR4/4	15	16.1	2.18	0.85	0.11	0.39	0.05	0.13	0.74	1.23	0.34	0.05	0.14
Closes variant 26CTP-80-20	Ap_2	13-32	10YR4/3	11	38.8	3.50	1.26	0.17	0.36	0.05	0.13	1.09	2.24	0.31	0.03	0.09
	Btkcn	32-64	10YR5/3	9	33.6	3.38	1.50	0.10	0.44	0.03	0.07	1.40	1.88	0.41	0.04	0.10
	Btkc	64-96	10YR5/6	18	20.9	3.61	1.74	0.10	0.48	0.03	0.06	1.64	1.87	0.45	0.08	0.17
	3Btkcn	96-130	10YR5/6	18	36.2	3.90	1.90	0.14	0.49	0.04	0.07	1.76	2.00	0.45	0.03	0.11

[1]R.I: Redness Index= [(25-nhue)* chroma]/value. Modified from Hurst, 1977; nhue value: 10YR=10; 7.5YR=7.5; 5YR=5; 2.5YR=2.5; 10R=0; [2]Clay: clay expressed in percentage, profiles B8-9 (Aspres) and B8-8 (Ventalló) previously carbonate-free particle size distribution; [3]Fe_t: digestion with hydrochloric+nitric (total); [4]Fe_{dt}: extraction with sodium citrate 17%+ sodium dithionite 1.7% (free); [5]Fe_{ox}: extraction with oxalic acid+ ammonium oxalate 0,2M, pH 3 (poorly crystalline).

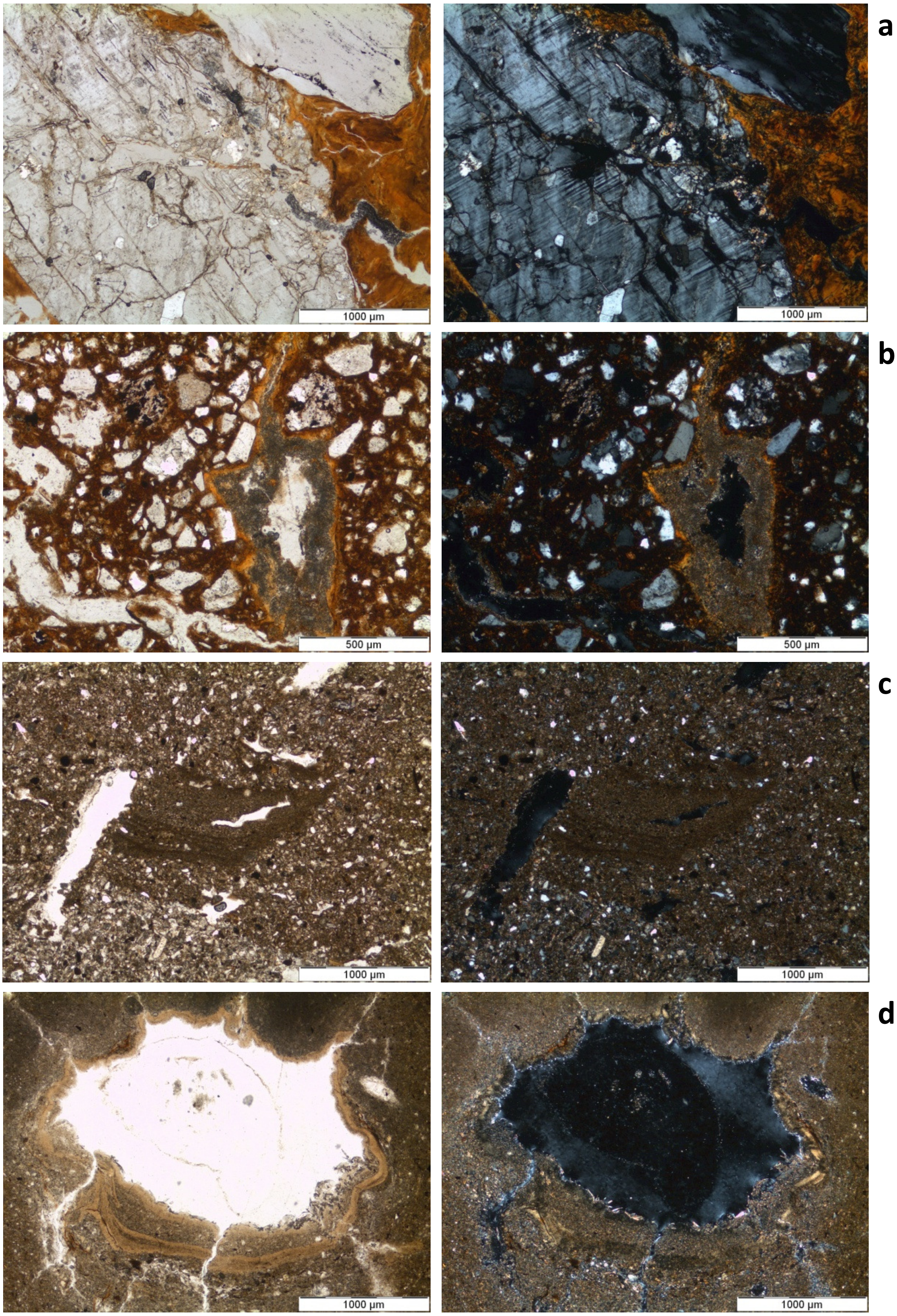

Figure 3.2. (a) Highly weathered plagioclases and deformed clay coatings, 4Bt, Aspres, profile B8-9 (b) Coating of micrite on a previous clay coating, 3Btkc$_2$, Ventalló , profile B8-8 (c) Fragment of layered material crust like, Bw$_3$, Armentera, profile B8-10 (d) Compound coatings of clay, silt and fine sand, 3Btkcn, 26CTP-80

The upper horizons from profile B8-8, down to 52 cm, contain randomly oriented limestone and calcareous petrocalcic fragments, some of them with internal laminated clay coatings in a decarbonated micromass. These features are compatible with a pedosediment as the parent material of these layers. At 52 cm there is a strong carbonation as a Bkm with secondary carbonates formed by micrite and needle calcite as pseudomorphs of plant remains. Coarse fragments are quartz grains, limestone and calcareous crust fragments. There is some clay mobilization at the upper part of the Bkm, probably due to a short-range illuviation just at its upper abrupt boundary coming from the upper, decarbonated horizon.

The groundmass of the underlying Bkm horizons from profile B8-8 is decarbonated. They are argillic horizons, calcium carbonate free, but with calcitic pedofeatures such as rhizocretions on clay illuviation features (Fig. 3.2b), that are sometimes broken by the calcite growths. Nevertheless, some fine clay coatings are found covering secondary calcite, which indicates that both processes (carbonation and clay illuviation) took place almost simultaneously within this horizon, acting at different microsites, e.g. carbonation of root channels due to biological activity while clay becomes dispersed and illuviated in patches of the decarbonated groundmass. In the deepest horizons carbonation is shown as fan-like carbonate crystals.

Redoximorphic features only appear below 60 cm at profile B8-8, as orthic, weakly impregnated nodules of Fe-oxihydroxides, both above and below the carbonate-cemented horizon. As in the Aspres series, their presence does not have any relation with the present porosity, therefore they should be considered as a palaeofeature.

Bt horizons of profile E-135 (Table 3.3) but also from Bt horizon in profile E-112 (Table S3.1) show a completely decarbonated micromass with a stipple-speckled b-fabric, and few microlaminated clay coatings as pedofeatures, from 50 cm down, around coarse fragments, that are mainly quartz and quartzites. At that depth very few impregnative hypocoatings of micrite, probably due to decomposed roots, are observed.

Armentera series (B8-10). Micromorphogically, the horizon differentiation in the Armentera profile is almost absent. It is material where the only pedogenic processes, apart from soil structure, are the faunal activity (pores as channels and chambers, star-like pores by coalescence of faunal excrements) and some short-range silt dispersion and accumulation in pores probably due to turbulent flow through macropore, deposition in faunal cavities and reworked by animals to the matrix (Fig. 3.2c) when these materials were at the surface. A remarkable feature is an incipient banded fabric formed by clay lamellae, probably inherited from the alluvial material. The soil is well drained and free from redoximorphic features throughout.

Closes variant (26 CTP-80). This soil shows features typical for alluvial–lacustrine- materials, as mixtures of fine and coarse materials, crust fragments and sorted materials, in a clustered, heterogeneous distribution. The redoximorphic pattern is mainly stagnic: nodules of Fe- and Mn-oxides within the aggregates, while most pores show Fe-depleted hypocoatings.

The upper part of the profile, with high exchangeable Na-saturation, shows features due to a low structural stability of the materials: vesicular porosity (due to air bubbles) and intercalations and compound coatings of clay, silt and even fine sand around pores (Fig. 3.2d). The lowermost calcic horizon has typical impregnating nodules of calcite, and coatings of small prismatic sparite crystals around pores.

3.4.3. Soils forming processes

Soil colour and rubefaction

Ventalló soils has a reddish colour (2.5YR-5YR), in the 2Bt horizon but also in the recalcified argillic horizon (Btk). In addition this profile is much redder than the Aspres profile. Aspres soils in the well drained profiles present similar colours. However profile B8-9, a somewhat poorly drained Aspres variant, has not such a red colour.

The red colours of these soils are attributed to the presence of hematite (Davey *et al.,* 1975), which gives red hues to soils (7.5YR and redder). Torrent *et al*. (1983) state that the colour could be used to predict the hematite content of the soils. Martín-García *et al.* (1998) also consider that the alternating drying and moistening, typical of Mediterranean climates, favour reddening through crystallization of iron oxides. Hematite has a much stronger pigmenting effect than goethite, and even at low concentrations of hematite the colour changes to redder than 5YR (Schwertman and Taylor, 1982). We may assume goethite is dominant in the less well drained soil from the Pliocene surfaces and this may be explained by the wetter condition of this soil (Schwertman and Taylor, 1982). Crystalline iron (Table 3.7) in higher in older soils than younger ones, but the results are not show a clear cut.

Neither the Armentera profile nor the Closes variant show brunification; the latter presents mottling due to redox processes. The lack of brunification may be explained because the soils are highly calcareous, the B horizon is not decarbonated and the brown colour due to poorly crystalline ferric oxides does not form (Duchafour, 1982).

Redoximorphic features

The observed redoximorphic features may be very old, for example the ones observed in the Aspres and Ventalló series. In the Closes variant they are related to the present void system and should be considered functional: mottling is present below 30 cm, and Fe concentrations and depletions are present with chromas of 2 or less. The Armentera series has no redoximorphic features and in the Aspres and Ventalló series mottles are present, in the latter below the petrocalcic horizon.

Translocation of carbonates

In the Aspres series carbonate accumulation is absent. When the parent material is calcium carbonate free. However in the Pliocene surfaces with calcareous rocks they develop a petrocalcic horizon.Not with standing a possible eolian origin of the carbonates in the Ventalló series, the sole presence of limestone gravels as skeleton in the petrocalcic horizon and upper horizons could be the source for the accumulations below. The petrocalcic horizon is moderately expressed. It shows a conglomeratic-like morphology under a laminated layer acting as contact with the overlying Bt horizon. The recarbonation of the underlying horizons is very strong. All the calcite in these horizons is present as pedofeatures and absent in the groundmass. Calcite nodules and infillings of micrite and sparite break previous clay coatings and disturb the original fabric in a process similar to the one reported by Gile and Grossman (1968), as it can be seen in the microphotographs of Figure 3.2b.

The origin of the calcitic concretions in the Closes variant is probably the water table, as has been explained for similar $CaCO_3$ accumulations in the area and in other places (Knuteson *et al.,* 1989). However the depth of accumulation suggests a double flow, upward and downward as Boettinger (2002). The fact that they are formed by micrite, and not by larger calcite crystals, suggests that they were recently formed, once the soil started to be drained (Durand *et al.,* 2010). Also the sodic conditions of the profile may enhance $CaCO_3$ acumulation. It is interesting to note the patchy distribution of this soil variant (Carrillo *et al.,* 1999), in association with soils without calcium carbonate concretions.

Only few pseudomycelia of calcite indicate very slight carbonate redistribution in Armentera series (not identified in thin section), and are not diagnostic as far as classification is concerned. These soils have a very high available water holding capacity (> 200 mm) which slows down the leaching of carbonates and, are in a young landforms.

Vertic properties

Besides the clay accumulation, the B8-9 profile soil shows the development of vertic features both in the field and in thin section, where slickensides are very evident (Fig. 3.2a). These features do not allow the identification of clay coatings in the 3Btss horizon due to the argilloturbation. The clay mineralogy does not agree completely with these observations, since smectite is a minor component and illite the dominant 2:1 clay (Table 3.8). However, this may be explained by the large amount of clay, as has been observed in other places where illite is also dominant and there are strong vertic features (Isbell, 1991; Imbellone and Mormeneo, 2011; Driese *et al.,* 2005; Kovda *et al.,* 2001). In our case the large content of coarse elements prevents the development of a true Vertisol and not all soils present such features; they seem to be more abundant in the clayey and poorly drained soils.

Some slickensides have also been observed in the most clayey soils of the Pleistocene terraces as well in the soil of the inner depressions (Table 3.1).

Table 3.8. Semi-quantitative clay mineralogy (X-ray diffracion) of selected horizons of *Baix Fluvià* soils (relative %)

Profile	Horizon	Depth	---- Minerals ----						
		(cm)	Quartz	Feldspar	Calcite	Goethite	Illite	Kaolinite	14Å
B8-9 Aspres	Ap_1	0-22	9	6	nd[1]	2	70	13	nd
	2Bt	33-55	tr[2]	tr	nd	3	72	25	smectite (tr)
	3Btss	55-80	tr	tr	nd	3	73	23	smectite (tr)
B8-8 Ventalló	Ap_1	0-23	6	5	tr	4	72	5	chlorite (8)
	2Bt	52-80	6	4	nd	2	80	8	nd
B8-10 Armentera	Ap	0-27	4	3	18	2	66	7	chlorite (tr)
	Bw_1	27-72	7	5	22	2	59	5	chlorite (tr)

[1]nd: non detected; [2]tr = traces

Clay and silt translocation

Clay illuviation in the Aspres soils is strongly expressed, mostly in the most gravelly / sandy horizons, as microlaminated clay coatings (B8-9 and E-30). The frequent deformation of such microlaminations and the fragments of clay coatings in the groundmass can be attributed to an ageing of the coatings (not functional at present) and to the argilloturbation, evident in the whole profile.

Illuvial clay is present as oriented coatings from 50 cm down in Ventalló soil (B8-8). The presence of numerous fragments of clay coatings and oriented clay in the groundmass, not related to present pores, shows that illuviation also occurred in the past. But the most evident feature supporting that is the relation between calcite and clay accumulation in the horizons under the petrocalcic horizon, where calcite coatings or infillings cover previous clay coatings, giving evidence of recarbonation (Fig. 3.2c).

The few silt coatings observed in thin sections in the Armentera series are probably inherited from the sedimentary parent material, although some of them are associated with the biopores.

The Closes variant has high sodicity (SAR: 21 to 76) and low salinity (ECe: 1.8 – 4.9 dS/m at 25ºC) (Table 3.9). These facts go together with a high alkalinity (HCO_3^- , CO_3^{2-}: 6.8 to 15.2 cmol(+)/L) and very low concentration of both Ca^{2+} and Mg^{2+}, (1.0 or less cmol(+)/L in the Bt horizons and slightly higher in the top soil: 5.7 cmol(+)/L); all this together produces a disruption of the soil structure. As a result, the micromorphological observations give evidence of translocation of Na-dispersed fine material, as silt or even a few oriented clay coatings (Fig. 3.2d). This, together with other features such as prismatic structures and clay- and Fe- depletion hypocoatings around pores, could indicate the natric character of the B horizons. Bulk density is also very high (data not presented).

Salinization and sodication

The Closes variant soil is located in a former large paludal area (Estany de Sant Pere), that was artificially drained. Probably the leaching of salts in the reclamation process led to their sodication and later alkalinisation. Porta *et al.* (1994) found similar soils in other parts of the Empordà Basin, showing similar processes of sodification.

Abrupt textural change

In the Aspres profile (B8-9) a lithologic discontinuity between the topsoil (Ap, A_2) and deeper horizons was described in the field. Notwithstanding the fact that there has been a strong new clay formation from weatherable minerals and an intense clay illuviation, changing the sand mineralogy and size distribution, both sand mineralogy (% of opaque and light minerals in the coarse sand, Table 3.6) and the clay-free coarse sand size distribution provide evidence of strong discontinuities that cannot be explained by these pedogenic processes alone.

In Ventalló soil (B8-9), the textural change between the top horizons (Ap, AB) and the underlying ones occurs together with a lithological discontinuity, evidenced by the particle size distribution of the clay-free fine earth. Besides, the sand mineralogy indicates other discontinuities within the Bt horizons. In this case it is clear that in many cases the addition of new material from upslope soils has taken place, also evidenced by the fragments of carbonate crusts, and therefore the textural change again may not be attributed only to clay illuviation.

Table 3.9. Soil salinity profile 26CTP-80 (Closes variant)

Profile	Horizon	Depth (cm)	Saturation moisture (%)	pHs[1]	ECe[2] (dS/m, 25ºC)	SAR[3] $(mmol/L)^{1/2}$	ESP[4] (%)	Salinity (saturated paste extract)(cmol/L)								
								Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO^{3-}	CO_3^{2-}	NO_3^{-}
26CTP-80-20	Ap_1	0-13	59.3	8.1	3.8	21.3	30	3.0	2.5	35.3	0.7	12.8	12.6	7.6	1.0	7.1
Closes variant	Ap_2	13-32	58.3	8.7	4.3	27.1	38	3.0	2.7	45.7	0.3	15.2	19.2	13.1	1.0	1.9
	Btkn	32-64	46.6	8.9	4.9	76.1	-	0.4	0.6	53.8	0.8	20.4	18.5	12.8	2.4	1.5
	Btkn	64-96	31.7	8.8	2.5	34.5	50	0.5	0.5	24.4	0.3	10.4	7.8	6.4	0.5	0.6
	2Btn	82-96	28.9	8.9	1.8	27.4	40	0.4	0.5	18.4	0.2	7.3	5.5	6.3	0.5	0.5
	3Btkn	96-130	61.6	8.6	2.9	38.3	57	0.4	0.8	29.7	0.2	13.1	9.6	6.9	0.5	0.4

[1]pHs: pH in saturated paste extract; [2]ECe: electrical conductivity in saturated paste extract; [3]SAR: sodium adsorption ratio; [4]ESP: Exchange sodium percentage comported according Richards (1969)

3.5. Discussion

3.5.1. Soil horizons, processes and soil-landscape relationships

In the different landforms studied, the soil processes acting in them and the resulting diagnostic features can be clearly related, which results in a firm soil-landscape model for the area. Carbonate translocation, clay illuviation and rubefaction, are the main forming soil processes; have been operating all the time in the studied profiles and landforms. However, the imprint is very different in the older (Pliocene and Pleistocene) than in the youngest (Holocene) ones; in the Pleistocene ones the geomorphological position has produced a very distinct morphology, with clear marks of poligenesis; soil in the Pliocene surfaces do not show addition of materials from runoff water and later pedogenesis. In any case eolian inputs may be discarded, and perhaps it explains the high base saturation of the soils from Pliocene surfaces, very different from the ones studied in Central Spain with a similar age a moister present climate (Gallardo *et al.,* 1987; Espejo, 1985). The most significant diagnostic horizons (i.e. calcic and argillic horizons) in the area may be due to very different processes and show very different morphologies, but the micromorphological and physicochemical studies have confirmed the field diagnostic. In none of the studied profiles are other epipedons than ochric present, nor are they in the study area.

Only the soils developed in the Pliocene surfaces on detrital, non-calcareous parent materials are now non-calcareous throughout. The Aspres series has an argillic horizon and an abrupt textural change, partly of pedogenic origin: in spite of that, clay illuviation is not very well exposed in the field, but the soil micromorphology shows fragments of clay coatings, deformed and fragmented, with the original microlamination disturbed by the argilloturbation, shown by the strongly striated fabric, related to the very high clay content. The Aspres series encompasses a wide range of Bt soil colour (2.5YR to 7.5 YR) and soil reaction (5.5-7.4, full data not shown). Other soils developed on Pliocene calcareous parent material always have some form of carbonate accumulation in the profile, although it may have a non-calcareous Bt.

Rubefaction is well expressed in both, the Aspres and the Ventalló series (2.5YR for the Bt horizons) although when recarbonation takes place it diminishes (5YR or less) or when the drainage is worse (B8-9) the redness decreases (B8-9). Erosion-sedimentation processes were very active in the Quaternary and as a result, in many of the soils in the Pleistocene, the surfaces have recarbonated argillic horizons (Palexeralfs, if they have a petrocalcic horizon), or in other cases the former clay-illuviated horizon may hardly be identified due to the strong erosion and recarbonation (petrocalcic or calcic horizon) and a Calcixerept is mapped. Even in other cases the former Alfisols are buried below 70 cm (Thapto-Alfic Xerofluvent, Grau series) (Table 3.1; data not presented). These soils are the ones which fit better in the concept of red Mediterranean soils, characterized by accretion and erosion of materials and latter pedogenesis (Fedoroff and Courty, 2013) and are similar from the point of view of iron characteristics to some of the ones reported by Bech *et al.(*1997). It is interesting to note the lack of Rhodoxeralf studied soils, only present in minor spots in the area (Table 3.1).

The Ventalló series has a textural change on top of the argillic horizon but it may be interpreted as a mixture of processes, both pedogenic and sedimentary. The presence of $CaCO_3$ in the soil matrix tells us that an addition of soil material has also taken place in this soil, from eroded upslope material. As a result of these processes the Ventalló series has an argillic, a petrocalcic and a nodular calcic horizon.

Both, Aspres and Ventalló series, present a textural change between A and Bt horizon. IN the Ventalló series such textural change may be explained, both, by a sedimentary process as well as the pedogenie one of clay illuviation. For the Aspres series the geomorphology and widespread presence of the abrupt textural change do not suggest the idea of a major role of sedimentation; the large amount of clay seems to be very difficult to explain only by translocation or in situ formation and the idea of Phillips (2007) of a multiply causality (bioperturbation, translocation) seems to be highly pertinent in our case. It is worthy to mention the abrupt textural change is not giving rise to a stagnic conditions, although some soils ahow a poorer drainage.

Pliocene surface soils show a progressive pedogenesis in all the cases according the model proposed by Johnson and Watson-Stegner (1987). Pleistocene surface soils have had, according the same model, stages of regressive and progressive pedogenesis.

The well-drained soils of the Holocene fluvial plain do not present any diagnostic endopedon (Armentera series). In these medium textured, very calcareous soils the identification of a cambic horizon is hampered by the lack of any visible carbonate removal on the Bw horizons, in spite of a very well developed soil structure. Also the age of the deposit, less than 2,000 years play a role.

The soils of the drained areas (Closes variant) have carbonate concretions (calcic horizons) which may be attributed to the drainage of the former lagoon. Theses profiles show a clear sodication process (ESP from 26-76%) with alkaline conditions (very high pH), that have led to the removal of divalent cations from the solution. These conditions, combined with the rather low salinity (ECe 1.8 dS/m in some horizons, Table 3.9) enhance the collapse of the structure and the dispersion of the fine material (silt and clay) in this soil. The illuvial pedofeatures are in many cases related to the present pore system. However these morphological and chemical characteristics do not suffice to identify a natric horizon because there is not enough clay increase with depth (SSS, 2014).

We should point out the poor geographical expression of some soil types in the area (Table 3.1), among them the Haploxeralfs and the soils with a cambic horizon. Likely, this is related to the poor extension in the area of suitable landforms of late Pleistocene or perhaps early Holocene age; younger landforms do not seem to be able to develop a cambic horizon such as the one demonstrated in the Armentera series.

3.5.2. Paleoenvironmental implications of the present soils

The studied soils do not conform to a chronosequence in the most strict sense but they may be regarded as one where the time factor (from a few hundred years to more than 2.5 M years) dominates the other pedogenetic factors (Huggett, 1998), in spite of the different nature of the parent materials. They allow us to see to what extent soil factors acting in the landscape can provide a clear view of the expression of the soil forming processes.

Calcium carbonate redistribution is a major process in the soils of the area. At this very moment the present soil water balance seems enough to prevent calcium carbonate accumulations in the non-calcareous soils (i.e. most the Aspres series and variant) and can even give rise to acidic topsoils (profile E-43; Table S3.2) and in general to counterbalance general or local eolian supply of this component in non highly calcareous soils .

It has been suggested that soils of southern Europe are affected, to one degree or another, by the dust transported from Africa (Muhs *et al.,* 2010), following the ideas presented much earlier by Yaalon (1987). In the study area Marqués *et al.* (2011) give a very detailed account of the existing sand dunes, and Sáinz-Amor and Julià (1999) describe their mineralogical composition. Àvila *et al.* (1996) have provided data about the dust in rains in the region, and Fiol *et al.* (2005) summarize the dust inputs in a much broader area in the West Mediterranean.

The lack of carbonate accumulations, the illuvial nature of the clay and the textural abrupt change at the topsoil of the Aspres series reinforce the idea of a non-eolian origin of these materials. This seems to support the idea that dust inputs, either from long or short distances, fall well below the range suggested by Yaalon (1987) that is incorporated into the soil (50 g/m^2 per year), in agreement with the data reported by Àvila *et al.* (1996).

Reddening of the soils, as is generally accepted, takes place after a full removal of carbonates (Duchafour, 1982), and only afterwards rubefaction occurs. The soils on Pleistocene surfaces but also the well drained in Pliocene surfaces show these phenomena in the highest degree, even in the soils that are fully recarbonated after this process. Some Aspres soils have been only partly reddened; this may be explained, to some extent, by poorer drainage conditions as is demonstrated by the redoximorphic features. Some authors (Vidal Bardán, 1993) have been claiming, in the Ebro Valley, a transport of already reddened materials for soils in similar latitudes but in other geomorphic positions, but this seems not to be the case in this area. It should be kept in mind that weathering is very much slowed down when $CaCO_3$ is present (Duchafour, 1982).

Aspres soils are developed in Pliocene surface (Julia, 2015 per.com.), in the absence of a more precise dating of these surfaces (Table 3.2). They have an strong abrupt textural change with a very coarse topsoil (sand and coarser quartz materials). We accept the high clay content of the B horizons comes from *in situ* neoformation in an already clay rich, gravelly parent material. Some micromorphological observations, such as bands of oriented clay within the schist fragments, following schistosity planes, suggest that at least part of the clay has been formed *in situ*, as observed also by Keller (1964) or Smeck *et al.* (1968) in other argillic horizons. In addition to that, clay illuviation has taken place, since the anisotropy and microlamination related to voids are very clear (Fig. 3.2a) and in the deepest horizons most of the fine material is oriented, as broken fragments in the groundmass, which indicates that the process has been acting for a long time. The abrupt textural changes are a proof of such illuviation and the long lasting process likely reforced, as Phillips (2007) suggest by biological activity. Also the higher amount of kaolinite demonstrates the higher degree of weathering of these soils.

The soils of the Pliocene surfaces (Aspres soils and variants) do not show the extreme development of the Pliocene soils (Espejo, 1985; Gallardo *et al.,* 1987) as kaolinitzation, planosolic character. These suggest perhaps the surfaces were not so olders or the (paleo)climate different.

The Ventalló soil shows, at least, a full cycle of decarbonation-reddening/clay illuviation-recarbonation-decarbonation (partly)-clay illuviation (older than Holocene). This is the situation of most of the soils on Pleistocene surfaces, attesting the above-mentioned soil erosion-sedimentation processes. They are linked to the position of these landforms in relation to the higher reliefs of Ventalló and Valldevià calcareous mountains and to the climatic oscillations of the Quaternary. The presence of a 2Bt over the petrocalcic horizon shows that the soil has undergone several climate cycles and successive erosion/addition of materials. The anorthic carbonate nodules and fragments of calcareous crusts, as coarse fragments on top of the petrocalcic horizon of the B8-8 profile could be considered to form a true stone line, and demonstrates the polycyclic nature of this soil. It indicates the existence of at least two cycles of illuviation separated by an erosional episode in this soil during the Pleistocene. Nevertheless, clay illuviation in this top 2Bt is by far not as well expressed as in deeper horizons. In the case of the Ventalló profile, carbonation is overprinting illuviation and rubefaction features, although in a few spots, mainly at the Bt – Bk horizon boundaries between Bt and Bk horizons, where fine clay coatings cover some carbonated features. The origin of the recarbonation is thus clearly alluvial from limestone and calcareous crust fragments. Our interpretation is that several periods (warmer temperatures) suitable for rubefaction have occurred during the Quaternary.

The polygenetic nature of red Mediterranean soils has been reviewed by Fedoroff and Courty (2013). According to them, clay illuviation, rubefaction and carbonate dissolution are assumed to take place during the wet interglacials, while carbonate accumulation would occur during drier periods. According to Fedoroff (1997) clay illuviation is a select feature under our present climate conditions, because such process is only taking place in the more humid borders of the Mediterranea basin. The clear microlamination of the clay coatings in Aspres and Ventalló soils – absent in Holocene Armentera and Closes profiles - points to past, more humid climates. These features, which are not always present in red Mediterranean soils (Reynders, 1972; Bresson, 1974; Lamouroux *et al.,* 1978) could have been preserved thanks to the accretional character of the parent material (Ventalló soils) subjected to a discontinuous genetic process (erosion/accretion); and to a period of rubefaction due to Fe release by mineral weathering and clay illuviation. In the Apres soils the same feature have been preserved across the climatic fluctuations of late Pliocene and Quaternary because no inputs of external material have reached these soils or in amount such that the soil is able incorporate into the profile without apparent profile retardation or simplification (Johnson and Watson-Stegner, 1987).

Wagner *et al.* (2015) presented an account about the pedogenetic process operating in the Western Mediterranean concluding the area experienced a subtropical climate since Early Pliocene and highlighted significant differences among the areas they studied (Baleric island and Granada basin). Ortiz *et al.* (2002) identifies in the last mentioned area periods of strong pedogenesis and demonstrate situation were soil characteristics allows data landforms. In our case the available data supports the idea of that pedogenic characteristics of landforms help to interpret their past history and it is a very rich proxy (Fedoroff and Courty, 2013).

3.6. Conclusions

The diagnostic features of the studied soils, both to identify soil forming processes and to define soil types, are clearly related to the landforms where they are located. These relationships have been established for the study area, and allows us to build up a good soil-landscape model. These facts also make soil correlation better, both in the field as well as in the office.

Carbonate translocation, clay illuviation and rubefaction are the main soil forming processes operating in the area. They are expressed in different manners according to the geomorphic surfaces, its age, its accretional / erosional evolution and finally to human influence.

The non-calcareous status almost all of the Aspres soils, developed on a Pliocene landform, with no more inputs than calcareous dust, seems to demonstrate that rainfall has been able, and is able at present, to remove the calcareous additions from the soil. However, in medium textured soils on Holocene – more recent - landforms, rainfall is not able to leach or even to mobilize the carbonates from the calcareous parent material to a significant extent. This fact strongly restricts the expression of cambic horizons.

A cambic horizon may be identified in soils with a calcic in older surfaces; while the cambic horizon of the Closes series is a special case derived from the drainage of the previous lacustrine, sodium-rich environment. The illuvial horizon of the Closes variant, in spite of the sodicity, does not qualify as a natric. The soils of the Pleistocene surfaces are polycyclic, with several (at least 2) cycles of erosion / colluviation associated to alternations of clay illuviation and recarbonation plus rubefaction. The older Pliocene soil does not express such phenomena because it has not received a significant input of new materials during its formation.

Supplementary material related to this article found, after references

References

Ávila A, Queralt I, Gallart F, Martín-Vide J. 1996. African dust over northeastern Spain: mineralogy and source regions, pp201-205. *In:* Guerzoni S, Chester R (Eds.). The impact of desert dust across the Mediterranean. Volume 11 of the Series Environmental Science and Technology Library. Springer Netherlands.

Bach J.1987. Sedimentación holocena en el litoral emergido de "L'Alt Empordà" (NE de Catalunya). *Acta Geològica Hispànica* **21-22**(1986-1987): 195-203.

Bailey EH, Stevens RE. 1960. Selective staining of K-feldspar and Plagioclase on rock slabs and thin sections. *American Mineralogist* **45**: 1020-1025.

Bech J, Rustullet J, Garrigó J, Tobías FJ, Martínez R. 1997. The iron content of some red Mediterranean soils from northeast Spain and its pedogenic significance. *Catena* **28**:211-229.

Benyarku CA, Stoops G. 2005. Guidelines for preparation of rock and soil thin sections and polished sections. Quaderns DMACS, 33, Universitat de Lleida, Lleida.

Boettinger JL. 2002. Calcification, pp 131-134, *In:* Encyclopedia of soil science. Marcel Dekker.

Boixadera J, Herrero J, Danés R, Roca J. 1989. Cartografía de suelos semiáridos de regadío: área regable de los canales de Urgell (Lérida), pp77 XVI Reunión de la SECS. DMCS-UDL & SECS.

Boixadera J, Herrero J, Danés R. 1990. Mapa de sòls detallat dels TM de Sant Pere Pescador, Vilamacolum, Ventalló, l'Armentera i Torroella de Fluvià (Alt Empordà). Draft report. DARP. Generalitat de Catalunya. Lleida, Spain.

Boulaine J. 1980. Pédologie appliquée, Coll. Sciences Agronomiques, pp. 220. Masson, Paris

Bresson LM. 1974. A study of integrated microscopy: rubefaction under wet temperate climate in comparison with Mediterraneanr ubefaction. *In:* Rutherford G. (Ed). *Soil Microscopy*. The Limestone Press, Kingston, Ontario, 526–541.

Carrillo G, Herrero C, Llop JM, Teixidor N, Boixadera J. 1999. Mapa de sòls (1:25000) del TM de Castelló d'Empuries (Alt Empordà). Draft report. DARP.Generalitat de Catalunya. Lleida, Spain.

CBDSA. 1983. SINEDARES, Manual para la descripción codificada de suelos en el campo. Ministerio de Agricultura, Pesca y Alimentación de España, Madrid.

DARP-ICC. 1993. Mapa de sòls de Catalunya 1:25,000 BELLVÍS. Departament d'Agricultura, Ramaderia i Pesca—Institut Cartogràfic de Catalunya.

Davey BG, Rusell GD, Wilson MJ. 1975. Iron oxide and clay minerals and their relation to colors of red and yellow podzolics soils near Sydney, Australia. *Geoderma* **14**: 125-138.

De Bruin S, Wielemaker WG, Molenaar M. 1999. Formalisation of soil-landscape knowledge through interactive hierarchical disaggregation. *Geoderma* **91**(1): 151-172.

Dijkerman JC. 1974. Pedology as a science: The role of data, models and theories in the study of natural soil systems. *Geoderma* **11**(2): 73-93.

Driese SG, Nordt LC, Lynn W, Stiles CA, Mora LI, Wildings LP. 2005. Distinguishing climate in soil record using chemical trends in a vertical climosequence from Texas coast prairie, and application to interpreting Paleozoic Paleosols in the Appalachian basin, U.S.A. *Journal of Sedimentary Research* **75**(3):339-349.

Duchaufour R. 1982. Pedology. Pedogenesis and classification (translated by Paton TR). George Allen and Unwin. London.

Durand N, Monger HC, Canti MG. 2010. Calcium carbonate features. Interpretation of micromorphological features of soils and regoliths. Elsevier, Amsterdam, pp. 149-194.

Espejo R. 1985. The ages and soils of two levels of “Raña” surfaces in central Spain. *Geoderma* **35**: 223-239.

Fedoroff N, 1987. Clay illuviation in red Mediterranean soils. *Catena* **28**: 171-189.

Fedoroff N, Courty MA. 2013. Revisiting the genesis of red Mediterranean soils. *Turkish Journal of Earth Sciences* **22**(3): 359-375.

Fiol LlA, Fornós JJ, Gelabert B, Guijarro JA. 2005. Dust rains in Mallorca (Western Mediterranean): their occurrence and role in sone recent geological processes. *Catena* **63**:64-84.

Fleta J, Escuer J. 1991. Sistemas sedimentarios del Alt Empordà y su relación con la tectónica y el vulcanismo. I Congreso Grupo Español del Terciario, Libro-guía Exc. 7, pp. 128.

Gallardo J, Peréz-González A, Benayas J. 1987. Paleosuelos de los piedemonte villafranquienses y las terrazas pleistocenes de la región del valle del Henares-Alto Jarama. *Boletín Geológico y Minero* **XCVIII-I**: 27-39.

Gile LH, Grossman RB. 1968. Morphology of the argillic horizon in desert soils of southern New Mexico. *Soil Science* **106**: 6-15.

Hole FD, Campbell JB. 1985. Soil landscape analysis. Routledgge and Kegan Paul. London.

Hudson BD. 1992. Soil survey as paradigm based science. *Soil Science of America Journal* **56**: 836-841.

Huggett RJ. 1998. Soil chronosequences, soil development, and soil evolution: a critical review. *Catena* **32**(3): 155-172.

Hurst VJ. 1977. Visual estimation of iron in saprolite. *Geological Society of America Bulletin* **88**: 174-176.

IGME. 1983. Mapa Geológico de España. Escala 1:50.000, 2 serie no 296. Torroella de Montgri. Serv. Publ. Ministerio de Industria., pp 45.

Imbellone P, Mormeneo L. 2011. Vertisoles hidromórficos de la planicie costera del Río de la Plata, Argentina. *Ciencia del Suelo (Argentina)* **29**(2): 107-127.

Isbell RF, 1991 Australian Vertisols. *In:* Kimble JM (Ed.). Proceedings of the 6th International Soil Correlation Meeting: characterisation, classification and utilisation of cold Vertisols. USDA, SCS. Washington, D.C., pp. 73-80.

IUSS Working Group WRB. 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Johnson DL, Watson-Stegner D. 1987. Evolution model of pedogenesis. *Soil Science* **143**(5): 349-366.

Keller WD. 1964. Processes of origin and alteration of clay minerals. *In:* Rich CI, Kunze GW (Eds), Soil Clay Mineralogy. Univ. of North Carolina Press, Raleigh, N.C.

Knuteson JA, Richardson JL, Patterson DD, Prunty L. 1989. Pedogenic carbonate in a Calciaquoll associated with a recharge wetland. *Soil Science Society of America Journal* **53**: 495-499.

Kovda I, Lynn W, Williams D, Chichagova O. 2001. Radiocarbon age Vertisols and its interpretation using data on gilgai complex in the north causasus. Proceedings of the 17th International 14C Conference, Carmi I, Boaretto E (Eds). *Radiocarbon* **43**: 603-609.

Lagacherie P, Legros JP, Burfough PA. 1995. A soil survey procedure using the knowledge of soil pattern established on a previously mapped reference area. *Geoderma* **65**(3) : 283-301.

Lagacherie P. 2008. Digital soil mapping: a state of the art. *In:* Hartemink AE. McBratney AB, Mendonça-Santos ML. (Eds.). Digital soil mapping with limited data. Springer Netherlands, 3-14.

Lamouroux M, Pinta M, Bouleau A. 1978. Expérimentation sur l'entraînement des produits dissous et en suspension dans un matériau fersiallitique. *Science du Sol* **1**: 55–71.

Legros JP. 1996. *Cartographies des sols: de l'analyse spatiale à la gestion des territoires* (Vol. 10). PPUR presses polytechniques.

MAPA. 1993. Métodos Oficiales de Análisis. Ministerio de Agricultura, Pesca y Alimentación de España, Madrid, Spain.

Margarit J, Muñoz P, Usón A, Boixadera J. 1993 Mapa de sóls del peu detallat (E:1:25000) del marge esquerra del Baix Ter. Draft report. DARP. Generalitat de Catlalunya, Lleida, pp 245+1 mapa.

Marquès MA, Julia R, Montaner J. 2011. Las dunas de la costa norte catalana, pp187-204. *In:* Sanjaume E, Gracia RS (Eds). Las dunas en España, pp 261. Sociedad Española de geomorfología . Fundación Empresa-Universidad Gallega.

Martinell J, Domènech R, De Gibert JM. 2000. Field trip Guidebook: Shallow Marine Macrobioerosion *In:*The Neogene of Catalonia. Third International Bioerosion Workshop, Barcelona.

Martín-García JM, Delgado G, Parraga JF, Bach J, Delgado R. 1998. Mineral formation in micaceus Mediterranean Red soils of Sierra Nevada, Granada, Spain. *European Journal of Soil Science* **49**: 253-268.

McBratney AB, Santos MM, Minasny B. 2003. On digital soil mapping. *Geoderma* **117**(1): 3-52.

Mehra OP, Jackson ML. 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. *Clays and Clay Minerals* **7**: 317-327.

Minasny B, Finke P, Stockmann U, Vanwalleghem T, McBratenney AB. 2015. Resolving the integral connection between pedogenesis and landscape evolution. *Earth-Science Reviewers* **105**:102-120.

Montaner J, Julia R, Castanyer P, Tremolesa S, Santos M, Riera S, Usera J, Sola J. 2014. El paleopaisatge fluvio-estuari d'Empuries. Sant Feliu de Guixols. *Estudies del Baix Empordà* **33**: 11-53.

Montaner J, Solà, J. 1998. Geological characteristics of the soils of the Empordà. *In:* Boixadera *et al.* (Eds). Tour Guide B8: Soil Information for Sustainable Development. 4.2-4.8. 16th World Congress of Soil Science. Montpellier. IUSS. Lleida.

Muhs DR, Budahn J, Avila A, Skipp G, Freeman J, Patterson D. 2010. The role of African dust in the formation of Quaternary soils on Mallorca, Spain and implications for the genesis of Red Mediterranean soils. *Quaternary Science Reviews* **29**: 2518-2543.

Ortiz I, Simón M, Dorronsoro C, Martín F, García I. 2002. Soil evolution over Quaternary period in a Mediterranean climate (SE Spain). *Catena* **48**: 131-148.

Phillips JD.2007. Development of texture contrast soils by combination of biturbation and translocation. *Catena* **70**:92-104.

Picart J, Solà J, Montaner J, Mató, Llenas M, Losantos M, Berástegui X, Agustí J. 1996. La sedimentación neógena en los márgenes de la cuenca del Empordà. *Geogaceta* **20**:84-87.

Porta J, Castelló E, Farras A, Velasco E. 1994. Els sòls dels aiguamolls de l'Empordà i estudi de les relacions sòl-vegetació. *In:* Gonzalbez J, Serra J, Velasco E (Eds), Els sistemes naturals dels aiguamolls de l'Empordà. Treballs ICHN. n.13, pp80-135, Barcelona, Spain.

Reynders JJ. 1972. A study of argillic horizons in some soils in Morocco. *Geoderma* **8**: 267–279.

Riba O. 1981. Canvis de nivell i de salinitat de la Mediterrània occidental durant el Neogen i el Quaternari. Treballs de la Institució Catalana d'Història Natural (filial de l'Institut d'Estudis Catalans) **9**: 45-62.

Richards LA 1969. Saline and alkali soils USSL. Riverside, pp. 160.

Sáinz-Amor EM, Julià R. 1999. Utilización de la mineralogía de arenas en la interpretación paleoambiental de las llanuras aluviales costeras: El Empordà, NE de la Península Ibérica. *Acta geológica hispánica* **31**(4): 55-66.

Samouëlian A, Cornu S. 2008. Modelling the formation and evolution of soils, towards and initials sysntesis. *Geoderma* **145**: 401-409.

Schwertman U, Taylor RM. 1982. Iron oxides, pp145-180. *In*: Discon *et al.* (Eds.). Minerals in soil environments. SSSA. Madison. Wisconsin.

Schwertmann, U. 1964. Differenzierung der Eisenoxide der Bodens durch photochemische Extraktion mit saurer Ammoniumoxalat-lössung. Z. Pflanzenernähr., Düng. Bodenkd., **105**: 194-202.

Serra J, Verdaguer A, Julia R, Marqués MA. 1994. Caracterització geologica dels aguamolls de l´Empordà. *In:* Gosalbez, J, Serra J, Velasco E (Eds) Treballs ICHN pp22-78. Barcelona.

SGC-ICC. 1995. Mapa geològic de Catalunya 1:25000. L'Escala Servei Geològic de Catalunya-Institut Cartogràfic de Catalunya.

SGC-ICC. 1996. Mapa geològic de Catalunya 1:25000. Sant Pere Pescador Servei Geològic de Catalunya-Institut Cartogràfic de Catalunya.

Smeck NE, Wilding LP, Holowaychuk N. 1968. Genesis of argillic horizons in Celina and Morley soils of western Ohio. *Soil Science Society of America Proceedings* **32**: 550-556.

SSS. 1993. Soil Survey Division Staff. Soil survey manual. USDA Washington, pp. 437.

SSS. 2014. Soil Survey Division Staff. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stoops G. 1987. Soil Mineralogy. Part II: Techniques. Lecture notes. ITC-Ghent, Belgium.

Stoops G. 2003. Guidelines for analysis and description of soil and regolith thin sections. Soil Science Society of America Inc. Madison, Wisconsin.

Torrent J, Schwertman U, Fechter H, Alferez F. 1983. Quantitative relationships between soil color and hematite content. *Soil Science* **136** (6): 354-358.

Vidal Bardán M. 1993. Los paleosuelos de las terrazas y glacis del sector riojano del Ebro. *Cuaternario y Geomorfología* **7**: 129-142.

Wagner S, Eckmeier E, Skowronek A, Günster. 2015. Quaternary paleosols and sediments on the Baleric islands as indicators of climate changes. *Catena* **112**:112-124.

Western S. 1979. Soil Survey contracts and quality control. Oxford University Press, pp. 292. Oxford.

Yaalon DH. 1987. Saharan dust and desert loess: effect on surrounding soils. *Journal of African earth Sciences* **6**(4): 569-571.

Supplemental material (Tables S3.1- S3.2)

Table S3.1. Morphological characteristics of the studied soils (Additional data)

Soil , profile number and classification (SSS 2014; IUSS WRB, 2014)	Horizon	Depth (cm)	Sand	Silt	Clay	Texture[1] USDA	Colour (moist)	R.I[2]	Coarse fragments ϕ^3 > 2mm (volume %)	Soil structure	Main features
			---------	(%)	-------						
Aspres series E-43 **Typic Palexeralf**	A_1	4-30	67.6	25.9	7.2	SL	10YR8/2	4	26-70	moderate, granular	unweathered quarzites. No mottles.
	A_2	30-45	64.7	22.9	6.9	SL	7.5YR7/6	15	26-70	moderate, granular	unweathered quarzites. No mottles
	A_3	45-60	63.6	22.6	9.3	SL	7.5YR7/6	15	>70	moderate, granular	many unweathered quarzites. No mottles
	Bt_1	60-80	35.9	13.4	50.1	C	2.5YR4/8	45	16-35	moderate, subangular blocky, medium	unweathered quarzites. No mottles
	Bt_1	80-100	54.3	10.5	34.7	SCL	2.5YR4/8	45	16-35	moderate, subangular blocky	unweathered quarzites. No mottles
	Bt_1	100-120	56.5	7.91	32.6	SCL	2.5YR4/8	45	16-35	moderate, subangular blocky, medium	unweathered quarzites. No mottles
	Bt_1	120-140	61.9	7.7	30.2	SCL	2.5YR4/8	45	16-35	moderate, subangular blocky, medium	unweathered quarzites. No mottles
	Bt_1	140-160	57.0	9.6	33.0	SCL	2.5YR4/8	45	16-35	moderate, subangular blocky, medium	unweathered quarzites. No mottles
	$2Bt_2$	170-180	68.0	11.4	20.1	SCL	2.5YR5/6	27	16-35	moderate, subangular blocky, medium	unweathered quarzites. No mottles
	$3Bt_3$	180-190	61.4	9.8	29.2	SCL	5YR4/8	20	16-35	moderate, subangular blocky, medium	unweathered quarzites. No mottles

[1]Texture USDA; L: loam; SCL: sandy clay loam; C: clay; SL: sandy loam; [2]R.I.: Redness Index= [(25-nhue)* chroma]/value. Modified from Hurst, 1977; nhue value: 10YR=10; 7.5YR=7.5; 5YR=5; 2.5YR=2.5; 10R=0 [3]ϕ: diameter.

Table S3.1. Morphological characteristics of the studied soils (Additional data) (cont.)

Soil , profile number and classification (SSS 2014; IUSS WRB, 2014)	Horizon	Depth (cm)	Sand ---------	Silt (%)	Clay -------	Texture[1] USDA	Colour (moist)	R.I[2]	Coarse fragments ϕ^3 > 2mm (volume %)	Soil structure	Main features
Aspres variant E-30 Palexeralf Chromic-Hypercalcic-Luvisol (cutanic)	Ap	0-28	71.0	15.6	13.3	SL	10YR5/3	9	15-35	subangular blocky	coarse fragments: gneiss and limestone
	Bt_1	28-53	56.0	14.1	29.8	SCL	7.5YR4/4	18	15-35	subangular blocky	coarse fragments: gneiss and limestone. Clay coatings. No mottles
	$2Bt_2$	53-87	67.4	9.6	23.0	SCL	7.5YR5/4	14	15-35	subangular blocky	coarse fragments: gneiss and limestone. Clay coatings. No mottles
	2Bkm	87-104	-	-	-	-	-	-	-	-	coarse fragments: gneiss and limestone. In the cemented petrocalcic horizon. Mottled in bands
Ventalló series E-112 Petrocalcic Chromic-Hypercalcic-Luvisol (cutanic)	Ap_1	0-26	72.8	15.9	10.4	SL	10YR4/4	15	<1	granular	no mottles
	AP_2	26-40	51.1	33.8	13.8	L	10YR4/5	19	<1	subangular blocky, medium	no mottles
	$2Bt_1$	40-60	51.9	29.5	17.7	L	7.5YR3/4	23	<1	subangular blocky	clay cutans. No mottles
	$2Bt_2$	60-119	40.8	26.8	28.6	CL	5YR3/4	27	<1	subangular blocky	clay cutans. No mottles
	3Bkm	99-120	-	-	-	-	-	-	-	-	strongly cemented petrocalcic horizon. Common Mn mottling

[1]Texture USDA; L: loam; SCL: sandy clay loam; C: clay; SL: sandy loam;[2]R.I.: Redness Index= [(25-nhue)* chroma]/value. Modified from Hurst, 1977; nhue value: 10YR=10; 7.5YR=7.5; 5YR=5; 2.5YR=2.5; 10R=0 [3]ϕ: diameter.

Table S3.2. Chemical characteristics of the studied profiles (Additional data)

Profile number and classification: Soil Taxonomy (SSS 2014) and *WRB (IUSS,2014)*	Horizons	pH[1] H_2O 1:2.5	EC[2] 1:5 (dS/m, 25ºC)	$CaCO_3$[3] eq. (%)	OC[4] (%)	CEC[5] (cmol(+)/ kg)	V[6] (%)	Exchangeable cations (cmol(+)/kg)			
								Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
Aspres E-43	O_2	-	-	-	7.3	-	-	-	-	-	-
	A_1	5.9	-		4.9	12.5	100	10.1	2.20	0.05	0.04
	A_2	5.1	-		-	3.3	29	0.5	0.40	0.02	0.06
	A_3	5.7	-		-	3.8	54	0.9	0.90	0.04	0.16
	Bt_1	5.7	-		-	20.7	76	11.51	3.75	0.19	0.23
	Bt_1	5.5	-		-	17.7	73	9.54	3.04	0.20	0.19
	Bt_1	5.7	-		-	13.9	75	7.64	2.42	0.16	0.19
	Bt_1	6.4	-		-	13.1	76	7.4	2.24	0.13	0.17
	Bt_1	5.8	-		-	11.8	71	6.14	1.86	0.24	0.15
	$2Bt_2$	5.8	-		-	6.9	100	5.7	2.00	0.07	0.21
	$3Bt_3$	5.6	-		-	10.7	100	8.0	3.10	0.12	0.26
Aspres E-30	Ap	7.0	-	-	2.1	-	-	-	-	-	-
	Bt_1	7.4	-	-	-	-	-	-	-	-	-
	Bt_2	7.7	-	-	-	-	-	-	-	-	-
Ventalló E-112	Ap_1	8.3	0.13	11.9	0.7	7.2	-	-	-	-	-
	Ap_2	8.3	0.15	13.1	-	6.8	-	-	-	-	-
	$2Bt_1$	8.5	0.10	3.4	-	17.5	-	-	-	-	-
	$2Bt_2$	8.6	0.11	3.8	-	15.3	-	-	-	-	-

CAPÍTOL 4:

Buried A horizons in old bech terraces in Les Garrigues (Catalonia)

Article published:

Boixadera, J., Riera, S., Vila, S., Esteban, I., Albert, R.M., Llop, J.M., Poch, R.M. 2016. Buried A horizons in old bench in Les Garrigues (Catalonia). *Catena* 137: 635-650. *DOI: 10.1016/j.catena.2014.08.017*

BURIED A HORIZONS IN OLD BENCH TERRACES IN LES GARRIGUES (CATALONIA)

Jaume Boixadera[1,2]; Santiago Riera[3]; Sílvia Vila[4]; Irene Esteban[5]; Rosa M. Albert[5,6]; Josep María Llop[2]; Rosa M. Poch[1*]
[1]Dept. Medi Ambient i Ciències del Sòl, U. de Lleida.
[2]Dept. Agricultura, Ramaderia, Pesca, Alimentació i Medi Ambient, Generalitat de Catalunya. [3]SERP, U. de Barcelona.
[4]Dept Història, UdL.
[5]ERAAUB. Dept. de Prehistòria, Història Antiga i Arqueologia. Universitat de Barcelona.
[6] ICREA Research Professor.
[*]corresponding author rosa.poch@macs.udl.cat

Abstract

A large part of Les Garrigues (Western Catalonia) is occupied by stone terraces (locally known as *bancals*) that were built up in the 18th century. Some soil surveys of the area noted the presence of buried, thick A horizons with a well developed crumb structure and darker colour than the present-day A horizons. The objective of this study is help to determine the conditions of the soil cover both at the time of the formation of these buried soils and at the onset of terracing.

The climate is semi-arid and the landscape is defined by platforms and flat-bottomed valleys. Four profiles from both slope and valley-floor terraces and sampled for analyses. A buried Ahb horizon appears at various depths between 40 and 180 cm, with thicknesses ranging from 35 to 160 cm, probably due to earthworks since this depends on the position of the profile within the terrace. Many of these buried soils would correspond to Phaeozems: they are identified by an Ahb having low values and chromas (usually 4 or less), a structure due to faunal activity (100% of the structural forms related to fauna either in the form of empty or infilled channels, vermic qualifier), and a organic matter content is 1.7-3.3%, which is higher but not significantly different than the SOM content of the present day topsoils, and P (Olsen) is 1-6 ppm.

The present soils are non-saline and highly calcareous (> 40%), they show some calcium carbonate redistribution in the form of pseudomycelia, and biogenic calcite. Charcoal is present in some of these buried horizons, together with small ceramic fragments. These buried horizons have several common micromorphological features: a spongy, highly porous structure due to a high faunal activity, frequent silt cappings, charcoal fragments, and biogenic carbonates (queras). In some cases the biogenic calcite has undergone dissolution and reprecipitated as micrite. Pollen assemblages of the buried horizons reveal a large forest cover mainly formed by oaks and pines, which is also corroborated by the occurrence of *Quercus* phytoliths; but the presence of pollen of some deciduous trees and crops (such as cereals, *Vitis sp, Olea sp*) at the top of the sequences point to a late Holocene origin of these soils. The results from the charcoal study support the presence of perennial *Quercus* and pines as well as shrubs when the terraces were built.

The available information about present day similar soils indicates that the formation of these horizons took place under a moister, milder climate in the past, compared with the present one in the study area.

Key words: Palaeosol, Western Catalonia, calcareous soils, semi arid Mediterranean, Holocene, Roman period, anthracology, phytoliths, pollen.

4.1. Introduction

A large part of the area of Les Garrigues county south of Lleida is occupied by stone terraces that are locally named *bancals*. These terraces are especially prevalent in the higher parts, close to Serra la Llena (Fig. 1). The terraced top soils do not display markedly different morphological features than the non-terraced counterparts, but some soil surveys of the area (Porta and Herrero, 1983; Carrillo *et al.,* 1998; IGC-DAAM-ICC, 2011; Boixadera *et al.,* 2012) noted the presence of a particular type of buried thick Ah horizon that was especially prevalent in infilled terraced gullies, and showed a very developed crumby structure and darker colour compared to present-day surface A horizons.

The *bancals* may be classified as contour and cross-channel terraces. They consist of dry stone walls, i.e. the stones are placed on each other without using cement, with heights ranging from less than one meter to more than 2.5 m. The flat slope type is dominant. These have a zero longitudinal slope and thus function as absorption terraces. The horizontal spacing between these terraces ranges from 2 to 3 m to tens of meters and their length occasionally reaches 100 m. In this area almost all the land is presently farmed with such a technique. Terrace walls are made with calcareous sandstones. Such rocks crop out as paleochannels in many places along the slopes, and the stones presumably were moved downslope in many cases (Martín and Serra, 1991). The staircase sequence of flattened parcels was created in order to harvest the runoff water by diverting the sediments. As in other dryland areas of the world, this stone-walled bench terrace system was constructed in order to create deep soils able to store scarce rainfall; irrigation was not considered due to the lack of available water.

According to Martín and Serra (1991) these terraces in the study area date from the 18th century and were linked mostly to the expansion of olive cultivation. Some local landlords (Duke of Cardona) pushed strongly for the plantation of olive trees in Les Garrigues, accelerating a sudden land use change over the region. Significant land use changes with large increases of the cultivated area took place in Valencia near to the study area, especially in the 18th and 19th centuries associated with an agrarian reform (Asins –Velis, 2006b).

Agricultural terraces occur in many parts of the world. The first general review was presented by Spencer and Hale (1961), and later significant reviews are from Vita-Finzi (1969), Denevan (2001) and Donkin (1979). Sandor (2006) provided a more recent account about their extent, function, building technique and land use significance. He noted the general scarcity of pedological studies on the terrace soils and commented on the need for more quantitative studies. Some of the studies that need to be mentioned about the genesis and properties of the terrace soils are Keeley (1985), Sandor and Eash (1995) and Eash and Sandor (1995) and Puy and Balbo (2013).

Buried soils are considered palaeosols when they are formed in a landscape of the past (Ruhe, 1956; Yaalon, 1971), or under changing environmental conditions (Bronger and Catt, 1989). When these buried soils have been affected by humans, archaeological techniques applied to soils may help to understand soil formation processes (Holliday, 2004). Therefore, the study of archaeopedological parameters is the correct approach in order to determine the human influence in the soil forming environment (Pietsch and Kühn, 2014). The study of the buried soils of the Garrigues terraces through this archaeopedological approach (Scudder et al., 1996) in order to determine the conditions of the soil cover both at the time of the formation of these soils and at the onset of terracing. These buried soils form an environmental archive that can be studied by comparative methodologies: macro-, micromorphological, and biomorphic analyses (charcoal, pollen and phytolith analyses, Golyeva, 2001), field evidence and carbon dating.

4.2. The physical environment

The studied region is located in the Western part of the Ebro Valley, south of Lleida, mainly the higher part of Les Garrigues county (Fig. 4.1) near the villages El Soleràs - La Granadella – Albagès - Bovera, covering more than 20 000 ha, at an altitude range of 160-526 m asl. The landscape features olive trees with some almond trees, and the region is characterized by dry soils in a semi-arid climate. The annual precipitation is 420 mm. The soil temperature regime is between mesic and thermic and the moisture regime of the soils (SSS, 2010) is xeric.

The landscape is dominated by caprock mesas composed of either calcareous alluvial Quaternary cemented gravel or Oligocene sandstone.

From a phytogeographical point of view, the South Lleida area is located in the transition between the climax areas of the continental maquia of *Quercus coccifera* and the woodlands of *Quercus rotundifolia.* The studied sector is close to the climax area of the termophilous continental maquia (Rhamno-Quercetum cocciferae subass. pistacietosum).

The natural vegetation is currently restricted to the stepper and rocky areas and the natural maquia in Les Garrigues has often disappeared. At present, the continental maquia (Rhamno-Quercetum cocciferae subass. cocciferetosum) alternates with remnants of the climax oak woods (dominated by *Quercus rotundifolia*) present among the agricultural fields. Other Mediterranean shrubs as *Juniperus oxycedrus*, *Arbutus unedo, Rhamnus alaternus, Erica multiflora*, are found, with the occurrence of *Lonicera implexa* and *Rubia peregrina*. In the shadow side some sub-Mediterraean species, as *Quercus faginea* or *Aphyllanthes monspelliensis* can occur. The pine (*Pinus halepensis*) was favoured for wood exploitation and is susceptible to wildfires, being the dominant tree type in some places. In the shadow side of the hills *Brachypodium retusum* pasture dominates; at the top of the hills (when not cultivated) the vegetation is dominated by the dwarf scrub community of *Rosmarinus officinalis* while the sun side is occupied by “espartars” (cat.) of *Lygeum spartum*. Nitrophilous vegetation proliferates at the field borders.

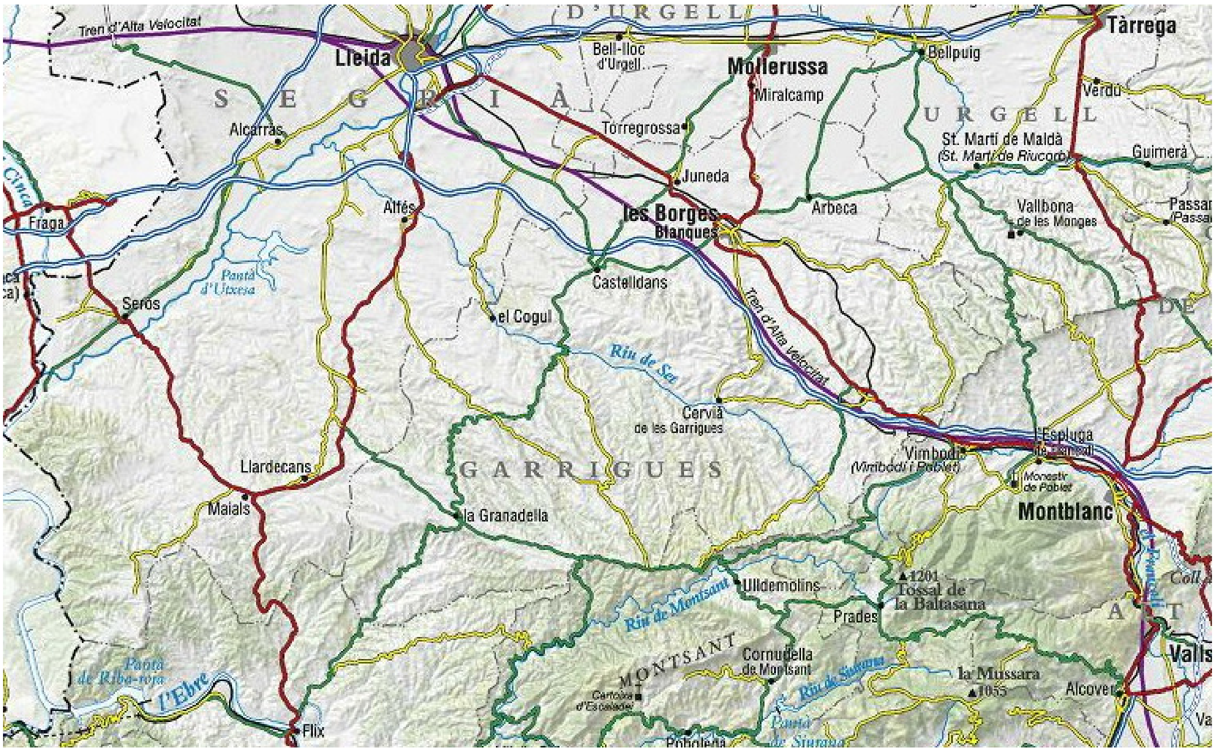

Figure 4.1. General map of the area south of Lleida. The red line is the limit of the *Denominació d'Origen* Les Garrigues for oil (*Apellation d'Origine Contrôlée*)

Soil genesis in the area is mostly controlled by the low leaching potential (Porta and Herrero, 1983) and the high calcium carbonate content of the parent materials. These greatly slows down the soil development (Boixadera, 1985), a very common occurrence under Mediterranean conditions (Jorda and Vadour, 1980). Soil structure development, a (slight) accumulation of organic matter and calcium carbonate redistribution are the main soil forming processes under these conditions, together with slope erosion and sedimentation processes giving rise to infilling of the bottom valleys.

The redistribution of calcium carbonate on young geomorphological surfaces is very limited. Only when the geomorphic surfaces are older is calcium carbonate accumulation significant (Porta and Herrero, 1983; Lewis *et al.,* 2009; Badia *et al.,* 2009) and in these cases the petrocalcic horizons control the development of the landscape (Julià and Marquès, 1983).

In the time span from the Bronze Age (700 BC) to present (described by Gutiérrez-Elorza and Peña- Monné (1998) as a geomorphologically stable period), the slopes do not show a significant soil development thus making the identification of a cambic horizon in these highly calcareous soils difficult (Boixadera *et al.,* 1989).

4.3. Methods

Three profiles from the Vall d'en Clarà (La Granadella), and one profile from El Soleràs (B8-2), located in terraces on infilled sloping gullies (GRA5, GRA8 and B8-2) and on a minor valley (GRA2) were described and sampled for chemical, physicochemical and micromorphological analyses. The three GRA profiles belong to the Vall d'en Clarà site, and were selected from 12 profiles previously studied by Seguí (2003). Their location is shown in Fig. 4.2. Separate samples were collected for biomorphic analyses (pollen, charcoal and phytoliths) and C14 dating (Table 4.1). In addition, information belonging to the Soil Survey of Catalonia from 45 profiles over the entire area was studied.

The soils were described and sampled according to FAO (2006). The methods described in Porta *et al.* (1986) for the physico-chemical analyses were followed. Particle size distribution was obtained without removal of carbonates.

Undisturbed blocks were taken from selected horizons of the sequences and vertical 5x13 cm thin sections were made following the procedures described in Benyarku and Stoops (2005). These thin sections were studied using a polarising microscope, according to the guidelines of Stoops (2003).

Pollen analyses were performed in eleven samples of the Ahb horizons and overlying Bw horizons of three profiles of the "La Vall d'en Clarà" site. The sampling scheme can be seen in Fig. 4.3.

Pollen extraction followed the classical physical-chemical treatment applied to palynology (Faegri and Iversen, 1989) with dense liquid pollen concentration (Goeury and De Beaulieu, 1979).

Two-hundred and fifty pollen grains in each sample were identified and the total basis for calculating the percentages included all the identified pollen grains and fern spores.

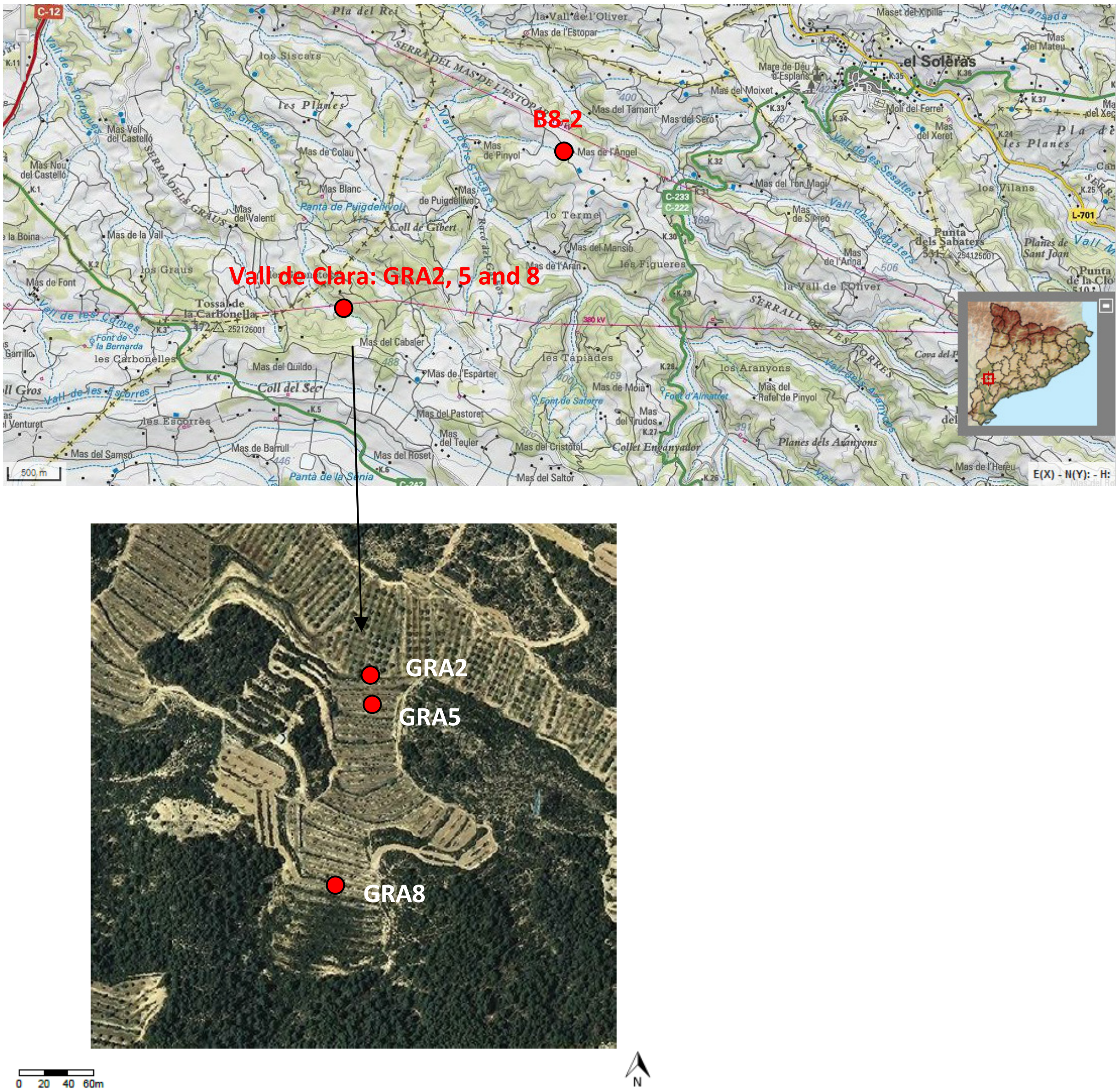

Figure 4.2. Location of the sampled profiles. Coordinates of "El Soleràs" (yellow circle): E(x): 306395.0 m, N(y): 4587456.0 m (UTM 31N/ED50)

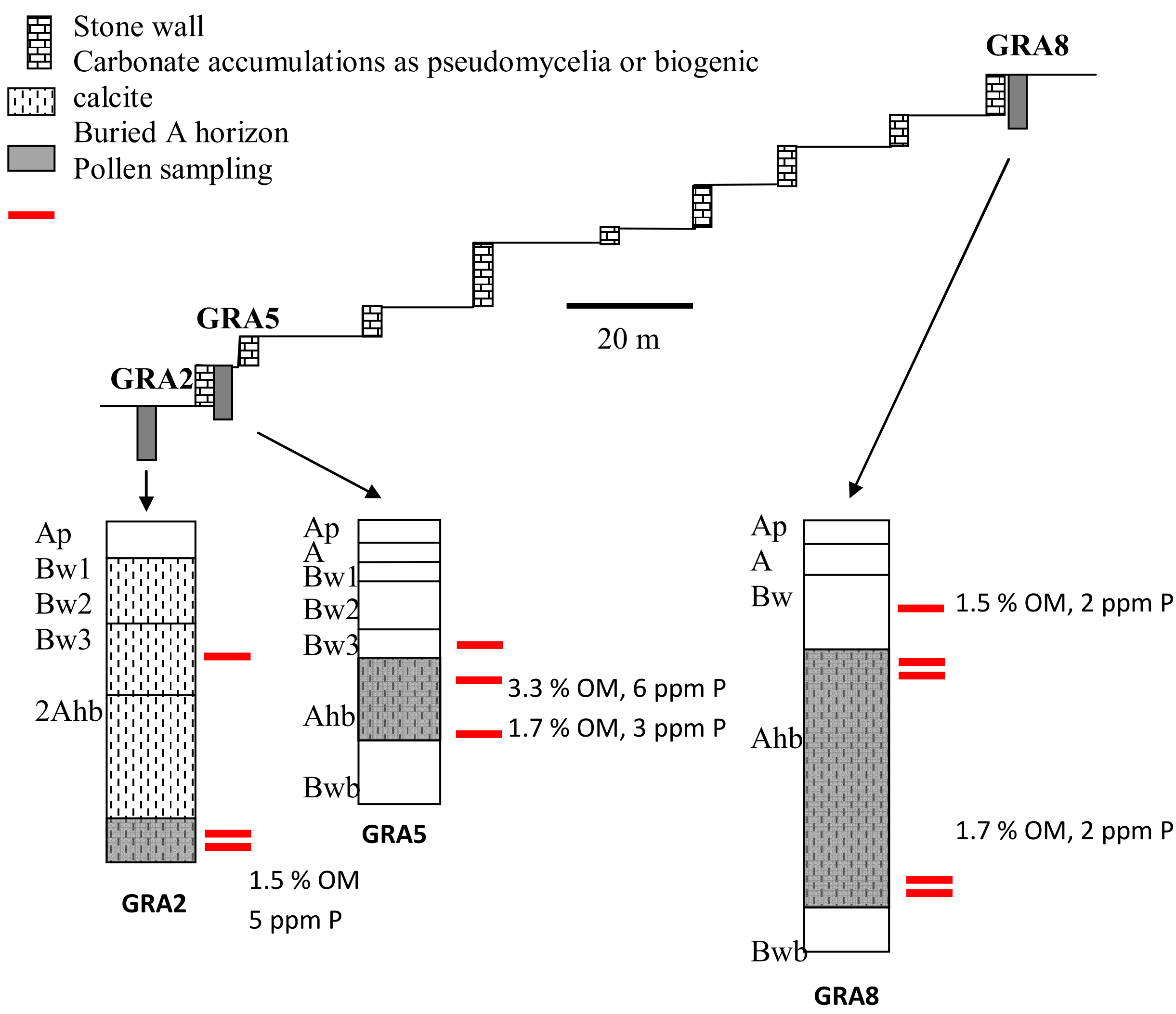

Figure 4.3. Sampling scheme. The red dashes indicate the locations of the samples for pollen analyses

The identified pollen taxa were grouped into the following categories: Tree pollen (AP), shrubs, herbs, crops and lastly weeds/nitrophilous taxa, a group that includes secondary anthropogenic indicators (Behre, 1981). The pollen type *Quercus ilex* t. includes the species *Quercus ilex, Q. rotundifolia and Q. coccifera*.

Six selected samples (Table 4.1) for anthracological analyses were taken and the charcoal fragments isolated by flotation. The identification of the genus and species was done according to Piqué (2006) and Schweingruber (1991).

The three anatomical planes of wood (transverse, radial longitudinal and tangential longitudinal) were studied with the aid of a binocular microscope, after anatomical preparation of the planes-by manual fracture.

Five samples (Table 4.1), from Ahb and overlying Bw horizons were analyzed for phytoliths following the extraction procedure described in Katz *et al.* (2010). Phytoliths were counted in 20 random fields at 200x and 400x magnification. Morphological identification was based on our modern plant reference collection (Albert *et al.,* 2011) and on standard literature (Mulholland and Rapp, 1992; Piperno, 1988, 2006; Twiss *et al.,* 1969). The International Code for Phytolith Nomenclature was also followed where possible (Madella *et al.,* 2005).

Table 4.1. Sampling strategy for the different analyses

Profile	Horizon	Pollen samples		Charcoal samples		Phytolith samples		C14 humus		C14 charcoal	
		code	depth (cm)	code	depth (cm)	code	depth (cm)	code	depth (cm)	code	depth (cm)
GRA2	Bw_2		60-105	1	80-120	3	60-105	1	100-120		
	2Ahb	1	180-190			1	180-190				
	2Ahb	3	200-210	2	180-205						
GRA5	Bw_3		75-95								
	Ahb	1	100-110			5	100-110				
	Ahb	2	135-145								
GRA8	Bw	3	40-90			3	40-90				
	Upper Ahb	sup1	90-100	Upper	90-120					1 charc	90-120
		sup3	110-120			1	110-120				
	Lower Ahb	inf1	210-220	Lower	210-240			2	210-240	2 charc	210-240
		inf3	230-240								
B8-2	Ahb_1			1	50-70						
	Ahb_2			2	90-110						

Three charcoal samples and the humus of two soil samples (Table 4.1) were selected for radiocarbon dating. The methods of chemical pre-treatment followed those used in the Oxford Radiocarbon Accelerator Unit, as described by Brock *et al.* (2010). Both NaOH-SOL fraction (humic acids) and total organic carbon (TOC) were analysed for each sample.

Dates were calibrated using Calib 7.0 based on Intcal 13 (Reimer *et al.,* 2013), and the ages at 0.95 probability as well as the interval age of highest probability were calculated.

4.4. Results

4.4.1. Soil properties

According to the available soil data base made with the profiles of the soil survey of the area, a buried Ahb horizon appears at depths between 40 and 180 cm in some terraced soils, under the present day surface, with thicknesses ranging from 35 to 160 cm. This high variability is probably due to the earthworks during terracing, since the thickness depends on the position of the profile within the terrace. They are prominent in infilled gullies and some minor valley bottoms. These buried horizons are identified by their low values and chromas (usually 4 or less). They have a medium to moderately fine texture, lack coarse fragments and have a distinct Ah morphology that is distinguished by granular structure with almost all the structural elements made by fauna, and are slightly darker than the underlying and overlying horizons. The comparison between colours of Ahb horizons and the corresponding present day surface Ap horizons of the same profiles (Fig. 4.4) show significant differences between values and chromas of both horizons. Almost all 45 profiles have a Bwb horizon below the Ahb horizon; there is a Bwkb (with soft calcium carbonate nodules) underneath in very rare cases. Pseudomycelia and queras (biogenic calcite, Herrero,1991), a common feature of most of these terrace soils, do not allow their qualification as a calcic horizon.

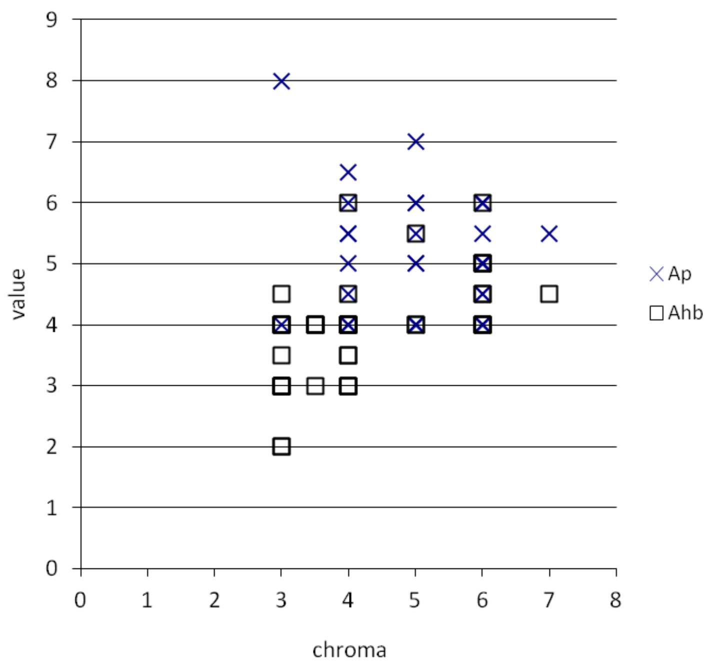

Figure 4.4. Values and chromas of the Ap and Ahb horizons of 45 soils on bench terraces of Les Garrigues having buried horizons. Average chromas (4.26 for Ahb – 5.19 for Ap) and values (3.95 for Ahb – 5.05 for Ap) of both genetic horizons are significantly different (p<1%)

The morphological and physico-chemical characteristics of the four selected profiles are shown in Tables 4.2 and 4.3.

The thickness of the Ahb horizons is highly variable at very short distances within a terrace. This is because the building technique involved some landfill and landcut along the slope and consequently some redistribution of the soil material. This caused the Ahb horizons at the edge of the terrace to be thinner than in its inner part, which was affected by landfill. The limit between the overlying horizon and the Ahb (Table 4.2) is generally smooth and clear; but also wavy or abrupt. We interpret both types of boundaries as the result of terrace building.

The field descriptions of these horizons show a high faunal activity, either in the form of empty or infilled channels that often determine the type of structure (100% of forms related to fauna). These characteristics of soil structure may allow for the use of the vermic qualifier (IUSS-WRB, 2006). The Ahb horizons are non-saline and highly calcareous (more 40%). Their organic matter content is 1.7-3.3% (organic carbon 1-1.9%), clearly higher than the corresponding present-day topsoils but not significantly different. Phosphorous (Olsen) ranges between 1 and 6 ppm, being in some cases a clearly indicator of an Ahb horizon. They show some calcium carbonate redistribution as pseudomycelia, and biogenic calcite is frequent and appears as queras (Herrero, 1991). Charcoal fragments are found in these Ahb horizons, together with some small ceramic fragments. Their distribution is very irregular: absent in some profiles (GRA 5) and present in small quantities in others throughout (GRA 2, GRA 8) or only in the Ahb (B8-2). Ahb horizon thicknesses, boundaries, charcoal and ceramics distribution point to some degree of human action and redistribution during the activities of terrace building. Spade or other tool marks have not been observed in the profiles.

Table 4.2. Field description of the selected profiles

Profile and horizon	Depth (cm)	Colour (moist)	Soil structure	Charcoal (ch) and ceramics (ce)	Accumulations	Lower boundary
GRA2						
Ap	0-20	7.5 YR 4/5	Moderate, subangular blocky, coarse	ch	-	Abrupt, smooth
Bw_1	20-60	7.5 YR 4/4	Moderate, granular, due to faunal activity	ch, ce	Pseudomycelia $CaCO_3$, abundant	Clear, smooth
Bw_2	60-105	7.5 YR 4/4	Moderate, subangular blocky, medium	ch, ce	Pseudomycelia $CaCO_3$, few	Clear, smooth
Bw_3	105-180	7.5 YR 4/4	Strong, due to faunal activity	ch, ce	Pseudomycelia $CaCO_3$, few	Abrupt, smooth
2Ahb	180-210	7.5 YR 3/3	Moderate, compound granular, fine	ch, ce	Silt coatings, abundant; Pseudomycelia $CaCO_3$, frequent	-
GRA5						
Ap	0-17	10 YR 5/6	Moderate, subangular blocky, medium	-		Abrupt, smooth
A	17-30	10 YR 4/6	Moderate, compound granular, fine	-		Clear, smooth
Bw_1	30-44	10 YR 4/6	Moderate, subangular blocky, coarse	-		Abrupt, wavy
Bw_2	44-75	7.5 YR 5/6	Weak, subangular blocky	-		Clear, smooth
Bw_3	75-95	7.5 YR 5/4	Moderate, subangular blocky, medium	-		Abrupt, wavy
Ahb	95-150	7.5 YR 3/4	Moderate, compound granular, medium	-	Pseudomycelia $CaCO_3$, few	Clear, smooth
Bwb	150-170	10 YR 4/6	Strong, subangular blocky, coarse	-		

Table 4.2. Field description of the selected profiles (cont.)

Profile and horizon	Depth (cm)	Colour (moist)	Soil structure	Charcoal (ch) and ceramics (ce)	Accumulations	Lower boundary
GRA8						
Ap	0-20	7.5 YR 4/4	Moderate, subangular blocky, medium	ch		Abrupt, smooth
A	20-40	7.5 YR 4/4	Moderate, subangular blocky, medium	ch, ce		Clear, smooth
Bw	40-90	7.5 YR 4/6	Moderate, subangular blocky, medium	ch		Clear, wavy
Ahb	90-250	7.5 YR 6/4	Moderate, compound granular	ch	Pseudomycelia $CaCO_3$, abundant (increasing with depth)	Abrupt, smooth
Bwb	250-265	7.5 YR 6/6	Weak, subangular blocky	-		-
B8-2						
Ap	0-19	7.5 YR 8/3	Weak, subangular blocky, medium	-		Abrupt, smooth
Bw	19-52	10 YR 5/6	Moderate, subangular blocky, medium	-		Clear, smooth
Ahb_1	52-73	7.5 YR 4/3	Primary: moderate, subangular blocky, medium; secondary: strong, granular, medium	ch		Clear, smooth
Ahb_2	73-109	7.5 YR 4/3	Primary: moderate, subangular blocky, medium; secondary: strong, granular, medium	ch	Pseudomycelia $CaCO_3$, few; Queras (biogenic carbonate), medium size, in pore channels, soft and discontinuous.	Clear, smooth
Bw	109-134	7.5 YR 5/6	Moderate, subangular blocky, medium	-		
2C	134-180	7.5 YR 5/6	-	-		

Table 4.3. Physico-chemical properties of the selected horizons

Profile and horizon	**pH_w (1:2.5)**	**EC (1:5) dS/m 25ºC**	**Organic Matter (%)**	**$CaCO_3$eq. (%)**	**P (ppm)**	**Sand 2-0.05 mm (%)**	**Silt 50-2 µm (%)**	**Clay <2µm (%)**	**Texture (USDA)**
GRA2									
Ap	8.2	0.32	4.3	40	6	27.8	48.5	23.7	SL
Bw_1	8.2	0.31	2.3	41	3	25.0	50.3	24.7	SL
Bw_2	8.1	1.37	1.4	43	2	29.1	48.7	22.2	L
Bw_3	8.1	1.50	1.4	46	2	28.4	48.6	23.0	L
2Ahb	8.6	0.32	1.5	46	5	26.3	49.5	24.2	SL
GRA5									
Ap	8.4	0.28	1.9	43	6	30.6	49.5	19.9	SL
A	8.2	0.29	2.1	41	2	30.0	47.9	22.1	L
Bw_1	8.2	0.31	1.8	44	2	34.8	44.8	20.4	L
Bw_2	8.3	0.28	1.1	46	2	47.7	34.4	17.9	L
Bw_3	8.4	0.24	1.0	43	2	47.3	35.9	16.8	L
Ahb	8.1	0.47	3.3	42	6	20.3	54.8	24.9	SL
Bwb	8.2	0.31	1.7	44	3	24.7	51.3	24.0	SL
GRA8									
Ap	8.3	0.22	1.1	46	2	21.7	39.2	39.1	L
A	8.5	0.22	1.2	48	2	20.3	42.1	37.6	L
Bw	8.4	0.24	1.3	46	2	16.3	36.2	47.5	L
Ahb	8.3	0.27	1.5	44	2	19.8	41.8	38.4	L
Bwb	8.4	0.27	1.7	43	2	21.4	47.8	30.8	SL
B8-2									
Ap	8.1	0.32	1.5	48	95	30.6	45.0	24.4	L
Bw	8.4	0.18	0.7	51	4	36.4	41.4	22.2	L
Ahb_1	8.4	0.16	1.0	48	3	39.4	37.6	23.0	L
Ahb_2	8.5	0.24	1.5	53	2	19.4	46.8	33.8	SCL
Bw_2	8.6	0.31	0.6	55	2	13.4	54.0	32.6	SCL

4.4.2. Micromorphology

The micromorphology of these Ahb horizons shows several common features: a spongy, highly porous structure due to a high faunal activity (Fig. 4.5a), frequent silt cappings (Fig 4.5b), charcoal fragments (Figs. 4.5c and d), and biogenic carbonates (queras, Herrero, 1991) (Figs. 4.5e, f, g, h). The latter are composed of infillings of biosparite in biopores, surrounded by a decarbonated hypocoating. This indicates a very short remobilisation of carbonates at a microsite scale. In some cases the biogenic calcite has undergone dissolution and reprecipitation in such a way that only the biosparite contour remains, formed by a line of microsparite crystals (Boixadera *et al.,* 2012).

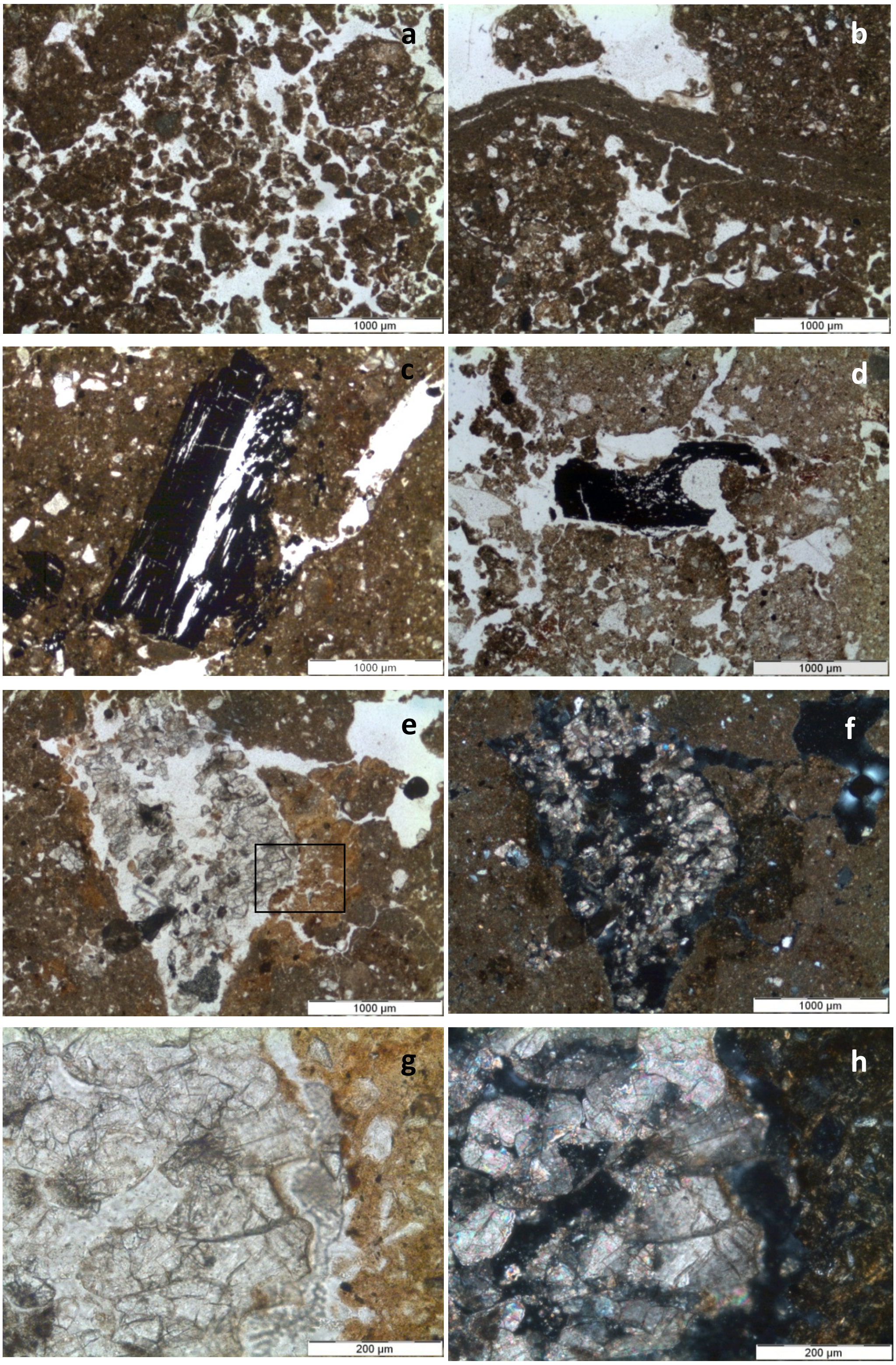

Figure 4.5. (a) Highly porous crumb structure of the buried A horizons, Profile GRA2, horizon 2Ahb, 180 cm. (b) Fragment of surface crust in Profile GRA5, horizon Ahb, 120-150 cm. (c) Charcoal fragments. Profile GRA5, horizon Ahb, 120-150 cm and (d) Profile B8-2, horizon Bw, 113-125 cm PPL. (e) Well-developed quera and detail (f), with decarbonated area at the left. Note the crystallinity of the biosparite crystals in the detail. These kind of well-preserved queras are seldom in the studied soils. Profile B8-2, Ab2 horizon, 75-85 cm. PPL and XPL

Textural features such as silt cappings and coatings (Fig. 4.6d) and depositional crusts (Fig. 4.6c) are observed. These features may have been associated with water flow inside the soil soon after terrace building, when the soil was still poorly arranged. Water flow through large macropores could also have been responsible. Silt cappings have been normally associated with buried, poorly-structured agricultural soils (McClung *et al.,* 2003; Adderley *et al.,* 2010), and have been identified in terraced soils from Greece with the same interpretation (French and Whitelaw, 1999). Charcoal fragments are also present.

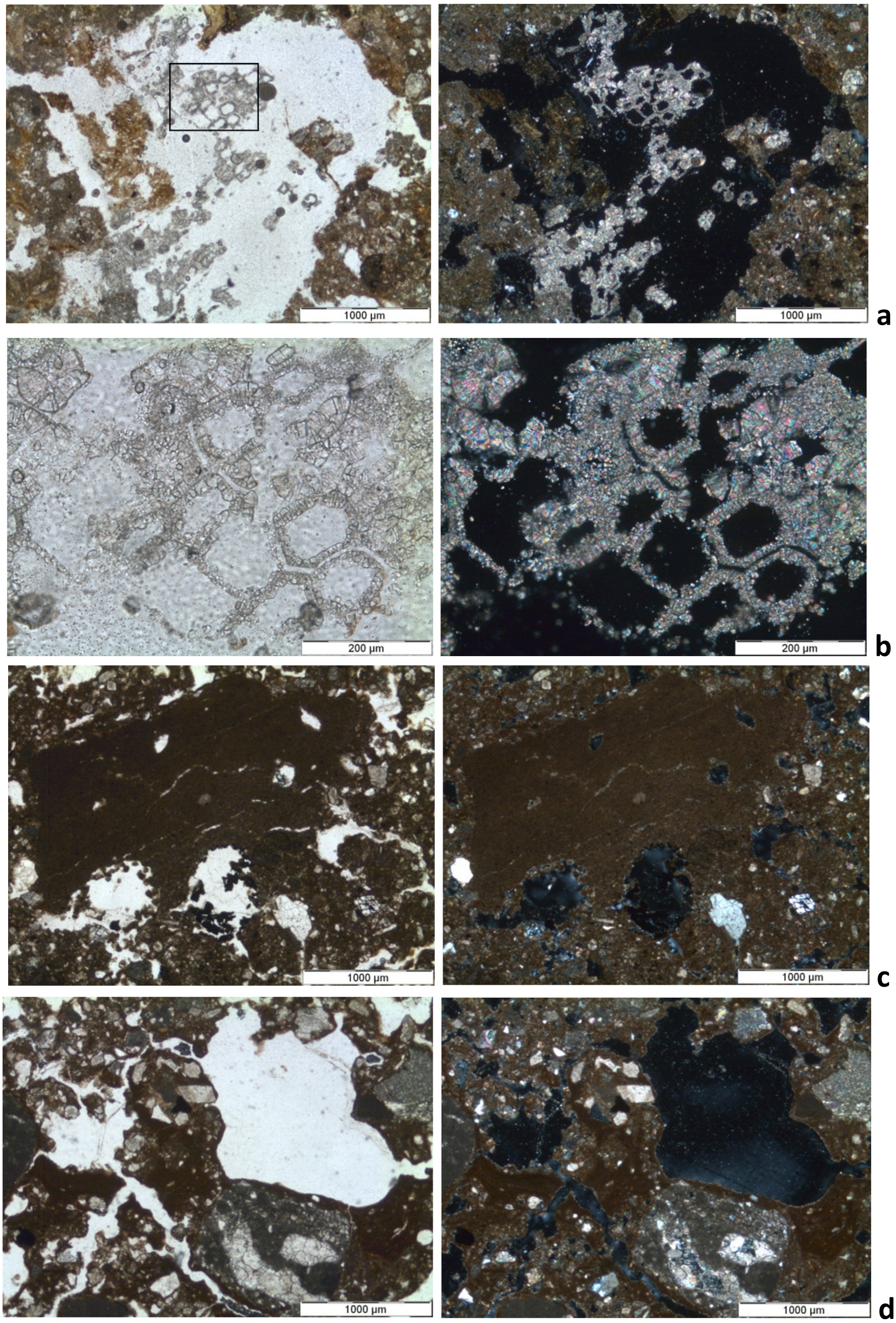

Figure 4.6. Micromorphological features of other profiles of the Vall de Clarà. (a, b) Partly dissolved biosparite and conversion to micrite moulds of former crystals, Profile GRA12, BCk horizon, 32-43 cm; (c) Fragment of sedimentary crust, deformed by faunal activity. Profile B8-5, Horizon Bw4 (100-140 cm). (d) Silt cappings and coatings around pores. Profile FIG3, horizon 2Ab (110-120 cm depth) PPL and XPL

4.4.3. Pollen

Pollen results are displayed in Table 4.4. In profile GRA2, pollen assemblages from the Ahb horizon are dominated by tree pollen (ca. 80%) that clearly decreases in Bw2 horizon (56%). In all the profile, the main woodlands are formed by pine (*Pinus*), with values of 37.8% in Ahb, decreasing to 17% in the Bw2 horizon; and evergreen oak (*Quercus ilex* t.), with mean percentages of 33%. Changes in pollen composition indicate an evolution of these main woodlands, consisting of a decline of *Pinus* (from 43.4 to 17%) and a first expansion of evergreen oaks, with pollen values increasing from 28 to 38% followed by a decrease to 30% in the Bw2 horizon. The presence of some deciduous trees is noticeable. Pollen percentages of shrub taxa are relatively low, *Erica* t. being the main recorded taxon with occasional occurrences of *Juniperus*, *Arbutus unedo*, *Cistus* and *Rosmarinus* t. Herb taxa Poaceae and Compositae record mean values of 12% in Ahb and 29% in Bw2, including *Artemisia* , Cichorioideae and Asteroideae as the main components of the herb stratum. The occurrence of weeds and ruderal taxa such as *Lotus* t., *Rumex*, Brassicaceae, *Plantago* and Chenopodiaceae is also remarkable. Pollen values of crops, such as *Cerealia* t. and *Olea europaea* are occasional, while *Vitis vinifera* is present in the Bw2 horizon.

Profile GRA5 shows similar pollen composition to GRA2. Here again, trees dominate the pollen assemblages of the Ahb horizon (mean values reach 76 %), decreasing in Bw3 horizon to a value of 43%. Wood communities are mainly formed by evergreen oak woodlands and pinewoods with a presence of deciduous oaks. The evolution of these woody communities is also similar to those reported in GRA2, with the general decrease of *Pinus* along the sequence (from 38 to 10%), an expansion of evergreen oaks along the Ahb horizon (from 34.7 to 43%) and a latter reduction in the overling horizon Bw3 (23%). Herb taxa values increase towards the top of the sequence (from 10 to 31.5%), including Poaceae (from 3.3 to 9.2%), Cichorioideae (from 0.3 to 11.4%) and *Artemisia*. In addition, the occurrence of weeds and nitrophilous taxa such as *Lotus* t., Brassicaceae, *Plantago*, *P. lanceolata* t., *Asphodelus*, *Polygonum aviculare* t. and Chenopodiaceae must be underlined as they suggest human activities. As in profile GRA2, in GRA5 the weeds increase in the Bw3 horizon, mainly *Plantago* and Chenopodiaceae. The increase of *Olea europaea* (3.3%) in the overlying Bw3 horizon is noticeable.

GRA8 also records a general decrease of tree pollen from ca. 80% in the lowest layers of Ahb horizon (210-220 and 230-240 cm depths) and 73.6% (90-100 cm depth) to 44.8% in the Bw horizon (40-90 cm depth). However, tree percentages show higher variability in the Ahb horizon. The main woody communities are similar to those reported in GRA2 and GRA5, with the dominance of evergreen oak and pine and the presence of deciduous oaks. Evergreen oak declines from 62.5% to

18.4% while pinewoods record a general increase between 230-240 cm and 90-100 cm (from 12 to 22% respectively) and a decrease in the upper sample of Bw horizon (18%). In this profile, *Erica* t., *Juniperus* and *Cistus* record the highest values of the studied samples. Herb taxa (mainly Poaceae, *Artemisia*, Asteroideae, *Carduus* t.,*Helianthemum* and Cyperaceae) are similar to those reported in GRA2 and GRA5 profiles. Their percentages increase at 110-120 and 40-90 cm depths, reaching the highest value of 43.4% mainly due to the highest representation of Cichorioideae in upper Ahb and Bw horizons.

Weeds and nitrophilous herbs are mainly reported in samples at 110-120 and 40-90 cm depths, with the presence of *Lotus* t., *Plantago* and *P. lanceolata* t and Chenopodiaceae. Rarer occurrences of *Euphorbia*, *Xanthium* t., Brassicaceae and *Polygonum aviculare* t. are reported over the whole profile. *Olea* (3.4%, the highest value of the sequence) *Cerealia* t. and *Vitis vinifera* are also present.

Table 4.4. Pollen composition of the studied samples

	Profile	**GRA2**				**GRA5**				**GR8**						
	Code	**Bw2**	**2Ahb1**	**2Ahb3**	**Total 2Ahb**	**Bw3**	**Ahb1**	**Ahb2**	**Total Ahb**	**Bw**	**Ahb Sup1**	**Ahb Sup3**	**Ahb Inf1**	**Ahb Inf3**	**Total Ahb Sup**	**Total Ahb Inf**
	Depth (cm)	60-105	180-190	200-210		75-95	100-110	135-145		40-90	90-100	110-120	210-220	230-240		
Trees	***Pinus***	17.0	31.7	43.4	38.0	9.8	20.4	37.8	31.0	17.8	22.0	18.3	19.2	12.1	20.0	16.0
	***Quecus ilex* t.**	29.8	37.9	27.9	32.7	22.8	43.0	34.7	38.0	18.4	45.1	37.5	56.7	62.5	41.8	59.3
	Deciduous *Quercus* t.	5.8	4.0	4.5	4.2	5.4	4.5	4.5	4.5	4.0	5.5	1.9	3.8	4.8	4.0	4.2
	Total *Quercus*	37.4	41.9	32.4	36.9	30.4	48.9	41.7	44.6	23.0	51.3	40.4	61.3	67.6	46.6	64.1
	Corylus		2.6	1.6	2.1	0.5		0.6	0.4	0.6	0.4	0.5		0.4	0.4	0.2
	Alnus	0.6	0.4	0.4	0.4			0.3	0.2				0.6			0.3
	Salix	0.6	0.4	1.6	1.1	2.2		0.3	0.2	2.3						
	Tilia		0.4	0.4	0.4											
	Ulmus		0.4		0.2											
	Tamarix			1.2	0.6					0.6						
	Betula									0.6						
	Total trees	55.6	78.0	81.1	79.6	42.9	69.2	80.7	76.1	44.8	73.6	59.1	81.1	80.1	67.4	80.7
Shrubs	***Juniperus***			0.4	0.2		0.5	0.6	0.5	0.6	0.7			1.1	0.4	0.5
	***Phillyrea* t.**		0.4	0.4	0.4											
	***Rosmarinus* t.**		0.4		0.2		0.5		0.2							
	Pistacia			0.4	0.2		0.5	0.9	0.7							
	***Erica* t.**	1.8	0.9	1.6	1.3	0.5	0.5	1.5	1.1	2.3	1.5	2.9	2.3	3.3	2.1	2.8
	Arbutus unedo			0.4	0.2		0.5		0.2					0.4		0.2
	Cistus			0.4	0.2	1.1	0.5	0.6	0.5	1.7	0.4		0.3		0.2	0.2
	***Ephedra fragilis* t.**						0.9	0.6	0.7			0.5			0.2	
	***Ephedra distachya* t.**					0.5		0.3	0.2		0.4		0.6		0.2	0.3
	Thymelaceae		0.4	0.4	0.4			0.3	0.2	1.1			0.6			0.3
	Total shrubs	1.8	2.2	4.1	3.2	2.2	3.6	4.8	4.3	5.7	2.9	3.4	3.8	4.8	3.1	4.2

Table 4.4. Pollen composition of the studied samples (cont.)

	Profile	GRA2				GRA5				GR8						
	Code	**Bw2**	**2Ahb1**	**2Ahb3**	**Total 2Ahb**	**Bw3**	**Ahb1**	**Ahb2**	**Total Ahb**	**Bw**	**Ahb Sup1**	**Ahb Sup3**	**Ahb Inf1**	**Ahb Inf3**	**Total Ahb Sup**	**Total Ahb Inf**
	Depth (cm)	60-105	180-190	200-210		75-95	100-110	135-145		40-90	90-100	110-120	210-220	230-240		
Weeds	***Lotus* t.**		0.4		0.2			0.3	0.2			1.0			0.4	
	Rumex		0.4	0.4	0.4	1.6				0.6						
	Brassicaceae		0.9		0.4	1.1		0.6	0.4	1.7				0.4		0.2
	Plantago	6.4	0.4	1.2	0.8	8.2	0.9	0.6	0.7	4.0		1.9		0.4	0.8	0.2
	Asphodelus		0.4		0.2		0.9		0.4							
	***Xanthium* t.**					0.5				0.6			0.6			0.3
	***Polygonum aviculare* t.**							0.3	0.2					0.7		0.3
	***Plantago lanceolata* t.**					1.1	0.5		0.2			1.0			0.4	
	Euphorbia										0.4				0.2	
	Chenopodiaceae	2.3	0.9	0.8	0.8	3.3	0.5	0.6	0.5	4.6	0.4	0.5		0.4	0.4	0.2
	Solanum	0.6														
	Total weeds	9.4	3.5	2.5	3.0	15.8	2.7	2.4	2.5	11.5	0.7	4.3	0.6	1.8	2.3	1.1
Herbs	**Poaceae**	7.0	4.0	4.5	4.2	9.2	5.9	3.3	4.3	6.3	2.6	2.4	2.0	2.9	2.5	2.4
	Artemisia	5.8	2.6	1.2	1.9	3.8	3.6	2.4	2.9	3.4	2.2	3.4	2.3	3.7	2.7	2.9
	Cichorioideae	7.0	0.4	1.6	1.1	11.4	3.2	0.3	1.4	14.4	11.4	19.7	0.6	0.7	15.0	0.6
	Asteroideae	3.5	2.6	1.2	1.9	2.2	2.7	0.6	1.4	2.9	1.8	1.0	2.0	1.1	1.5	1.6
	***Carduus* t.**	1.8	0.4	0.4	0.4	0.5		0.9	0.5	0.6	0.7	2.9	0.9	1.1	1.7	1.0
	Helianthemum		0.4		0.2	0.5	2.3	0.6	1.3	1.1	1.1	1.4	2.9	0.7	1.2	1.9
	***Centaures solstitialis* t.**		0.4	0.4	0.4	0.5					0.4	0.5		0.4	0.4	0.2
	Apiaceae	0.6	0.4	0.8	0.6	1.6	0.5	0.6	0.5	1.7		0.5		0.7	0.2	0.3
	Ranunculus		0.4		0.2											
	Cyperaceae	2.3	1.3		0.6	1.1	2.7	0.9	1.6	1.1	0.7	1.0	1.5	0.7	0.8	1.1
	***Trifolium* t.**	0.6				0.5										
	Fabaceae	0.6														
	Total herbs	29.2	13.2	10.2	11.7	31.5	20.8	9.7	14.1	31.6	20.9	32.7	12.2	12.1	26.0	12.2

Table 4.4. Pollen composition of the studied samples (cont.)

	Profile	GRA2				GRA5				GR8						
	Code	Bw2	2Ahb1	2Ahb3	Total 2Ahb	Bw3	Ahb1	Ahb2	Total Ahb	Bw	Ahb Sup1	Ahb Sup3	Ahb Inf1	Ahb Inf3	Total Ahb Sup	Total Ahb Inf
	Depth (cm)	60-105	180-190	200-210		75-95	100-110	135-145		40-90	90-100	110-120	210-220	230-240		
Crops	Cerealia t.	0.6	0.9	0.8	0.8	0.5				0.6			0.3			0.2
	Olea europaea	0.6	0.9	0.4	0.6	3.3	0.5	0.9	0.7	3.4	0.4		0.9	0.4	0.2	0.6
	Vitis vinifera	1.2								0.6	0.4		0.3		0.2	0.2
	Total crops	2.3	1.8	1.2	1.5	3.8	0.5	0.9	0.7	4.6	0.7		1.5	0.4	0.4	1.0
Ferns	*Polypodium*		0.9		0.4		0.9		0.4							
	Trilete	1.2	0.4		0.2	2.7	2.3	0.9	1.4	1.1	1.1	0.5	0.9	0.4	0.8	0.6
	Monolete	0.6		0.8	0.4	1.1		0.6	0.4	0.6			0.0	0.4		0.2
Total pollen		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

4.4.4. Anthracology

Six samples of charred wood from the horizons shown in Table 4.5 were studied. Sixty-seven fragments of charcoal were analyzed, of which 40 fragments were taxonomically determined. The high number of unidentified fragments (27) is mainly caused by their small size (Fig. 4.7) but also by anatomical abnormalities such as cracks, vitrification or fungi (Fig. 4.7h) that distort the identification. For this reason, they will be ignored in the discussion of results.

Table 4.5. Identification of charcoal fragments in the selected samples for anthracology. Figures refer to counts

Taxon	**B8-2/1**	**B8-2/2**	**GRA2/1**	**GRA2/2**	**GRA8 upper**	**GRA8 lower**	**Total**	**Total identified %**
Coniferae		1		1			2	5.0
Juniperus sp.					1		1	2.5
Monocotyledoneae					1		1	2.5
Pistacia lentiscus						1	1	2.5
Quercus sp. (root)					3		3	7.5
Evergreen *Quercus* sp.					2		2	5.0
Rosmarinus officinalis					30		30	75.0
Unidentified	1	1	3	2	20		27	
Total analyzed fragments	**1**	**2**	**3**	**3**	**57**	**1**	**67**	
Total identified		**1**		**1**	**37**	**1**	**40**	**100**

The taxonomic diversity is determined by six species belonging to Conifera, *Juniperus* sp. Monocotyledoneae, *Pistacia lentiscus*, evergreen *Quercus* (oak) and *Rosmarinus officinalis* (Fig. 4.7).

According to the amount of fragments per taxa, *Rosmarinus officinalis* is the most frequent species (30) accounting for 75% of the total number of identified fragments. It is followed by *Quercus* sp. (3 fragments, 7.5 %); evergreen *Quercus* and Coniferae (2 fragments, 5%); *Juniperus* sp., Monocotyledoneae and *Pistacia lentiscus* (1 fragment each, 2.5 %).

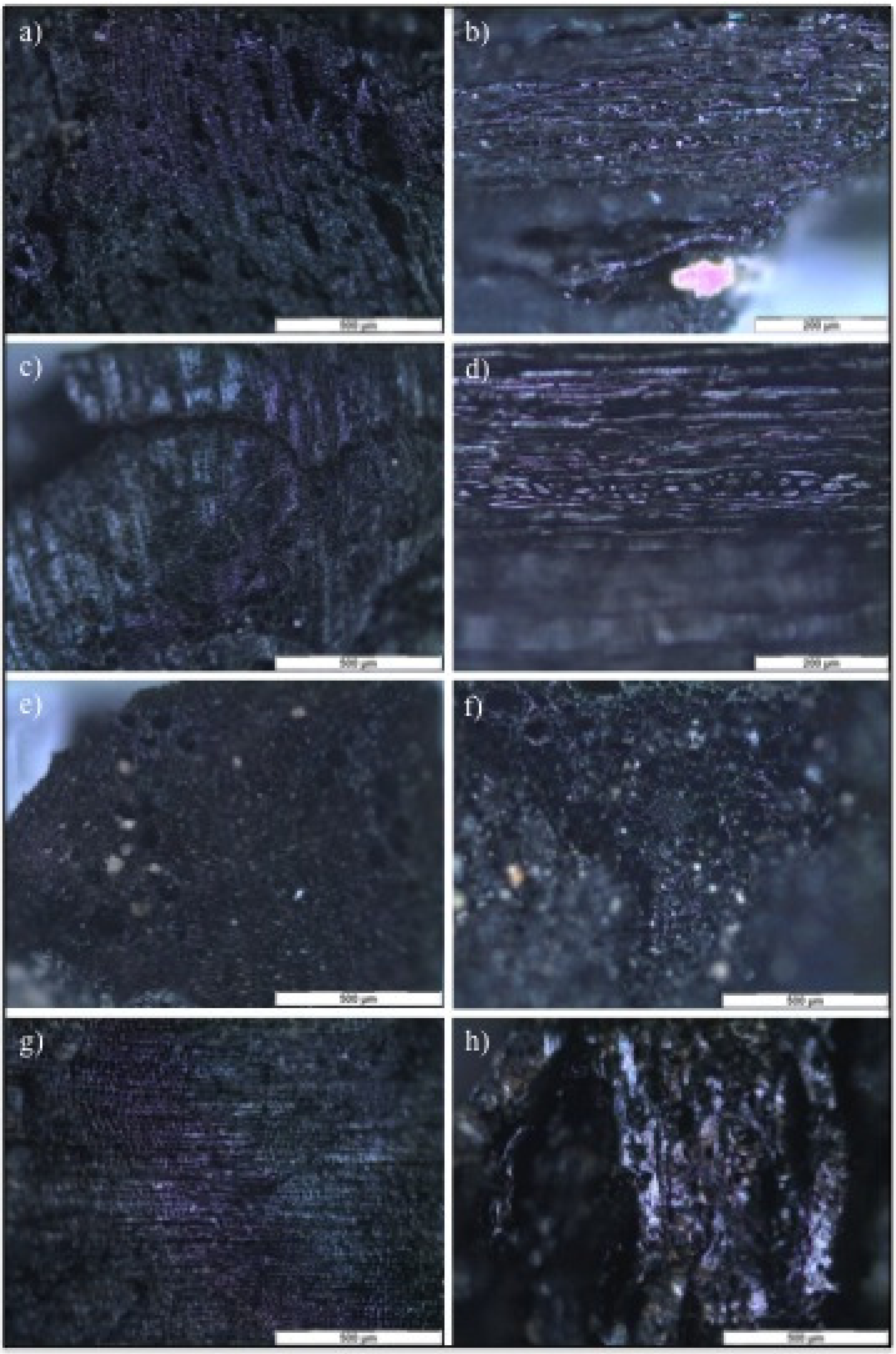

Figure 4.7. Images of charcoal fragments of this study. (a) Cross section of *Pistacia lentiscus* (GRA2/2). (b) Tangential section of *Pistacia lentiscus* (GRA2/2). (c) Cross section of *Rosmarinus officinalis* (GRA8 lower). (d) Tangential section of *Rosmarinus officinalis* (GRA8 lower). (e) Cross section of evergreen *Quercus* (GRA8 lower). (f) Cross section of Monocotyledoneae (GRA8 lower). g) Cross section *Juniperus* sp. (GRA8 lower). (h) Cross section of an undetermined fragment (GRA2/1)

4.4.5. Phytoliths

The main results of the phytolith analysis from the five samples are listed in Table 4.6. Phytoliths were identified in low concentrations and thus results should be taken with precaution (Albert and Weiner, 2001).

All the phytoliths identified in the Ahb horizons come from both the leaves and wood and bark of dicotyledonous plants.

Table 4.6. Phytolith quantitative and morphological results

Profile and horizon	Phytoliths g/sed	Short cell rondel	Trapezi -form	Prickle	Elongate morpho-types	Irregular	Multicell polyhedral	Sponge spicule
GRA2								
Bw_2	0	-	-	-	-	-	-	-
2Ahb	7,000	0	0	0	1	1	4	0
GRA5								
Bw_3	20,000	1	2	1	2	0	0	0
GRA8								
Bw_1	0	-	-	-	-	-	-	-
Ahb	20,000	0	0	0	0	0	2	1

Silicified multicellular polyhedral structures were identified in samples of the Ahb horizons (Fig. 4.8 b, d, e, f). These morphotypes correspond to the epidermal tissue of leaves of dicotyledonous plants (Piperno, 1988, 2006) and morphologically resemble to those of *Quercus* (Albert and Weiner, 2001). Further, polyhedral forms are absent from pines (Albert and Weiner, 2001). Multi-cell or interconnected phytoliths are fragile and do not always appear in the archaeological record. Thus, their identification in those samples suggests relatively stable chemical environments that prevented them from dissolution. In addition to the polyhedral leaf-phytoliths, parallelepiped and irregular forms (Fig. 4.8 a, c), that are common in the wood and the bark of trees have been identified.

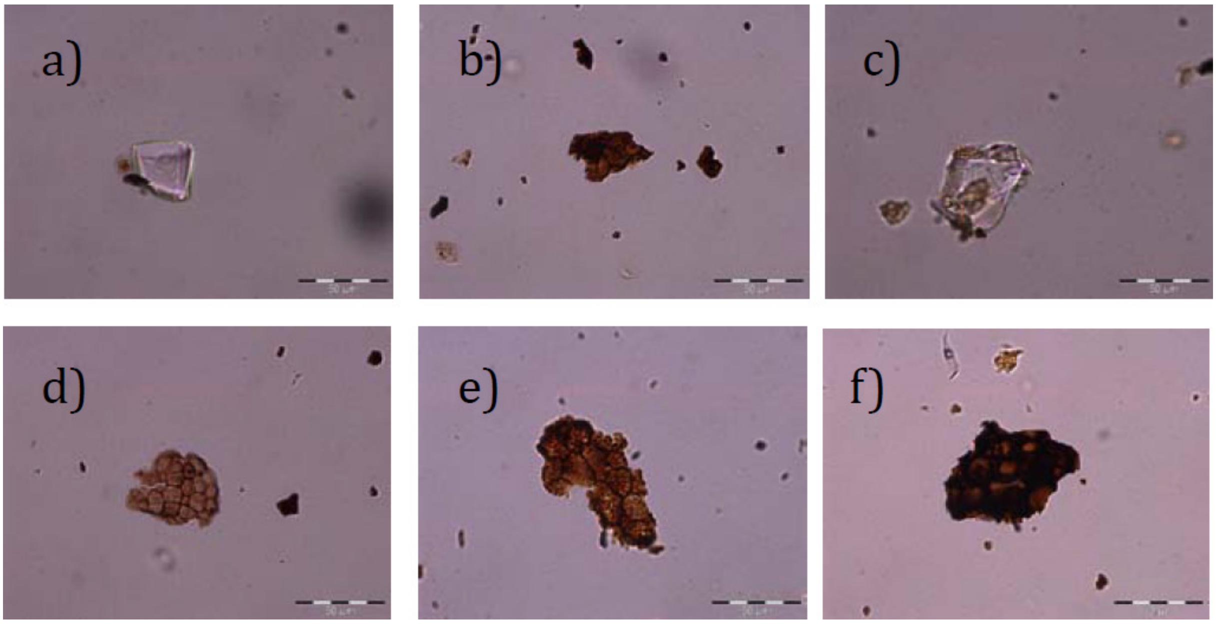

Figure 4.8. Photomicrographs of phytoliths identified in archaeological samples from the agricultural terraces of Les Garrigues. (a) Parallelepiped with square edges of the sample GRA2/1. (b) Multicellular structure with polyhedral silicified sample surface GRA2/5. (c) Irregular shape of the sample GRA2/1. (d, e, f) Silicified multicellular structures with polyhedral surface of the sample (d, e) GRA2/1, (e) and (f) GRA8/1

Phytoliths are absent in horizons Bw2 of GRA 2 and Bw of GRA 8, and their content is very reduced in horizon Bw3 of GRA 5. The phytoliths identified in this latter sample were derived mostly from grasses. Among them, the identification of short cell rondels and trapeziforms points to the dominance of C3 Pooideae grass subfamily typical from temperate environments as the Mediterranean.

The absence of phytoliths in the Bw horizons of GRA 2 and GRA 8 and the very low number of phytoliths in Bw3 horizon of GRA 5 is noticeable. Grasses produce more than 20 millions phytoliths per gram of material, and thus in stable environments they should be preserved in much higher numbers. In any case, other predepositional aspects such as soil, vegetation removal or fast deposition of the parent material may have also been responsible for the low phytolith presence.

4.4.6. Dating

14-C dating was applied to the best-preserved charcoal fragments (*Rosmarinus sp, Pistacia lentiscus*) of profile B8-8, and also to the humus of two Ahb horizons of profiles GRA8 and GRA2. The results are shown in Table 4.7.

The calibrated ages of the charcoal fragments from the top parts of Ahb horizons which were probably added during the period of terrace building, are consistent with the historical records of the terrace-making period in the 18^{th} century. Burning of vegetation should have been practised before terracing, hence the numerous charcoal fragments found in the buried horizons. The presence of a lens with high charcoal content in one of the profiles (data not presented) confirms this hypothesis.

The measured humus ages are found in the cal age between 194 BC and 388 AD. The Ahb horizon of profile GRA8 shows the largest difference (433 years) between the ages of the humic acids (younger) and the rest of the OM (older). On the contrary, humic acids of sample GRA2/1 are older than the residue of OM. The $\delta^{13}C$ values, although only approximate (obtained after graphitisation of the samples and via an AMS spectrometer, implying important isotopic fractionation) are consistent with C3-type vegetation.

Table 4.7. C-14 ages of charcoal fragments (*Rosmarinus sp, Pistacia lentiscus)* and humus samples. Humus dating refers to humic acids extracted with NaOH (*) or humin (**). Calibration was performed with Calib7.0, dataset: Intcal13.14c (Reimer *et al.,* 2013)

Horizon and code	Horizon	Depth (cm)	Lab. no.	$\delta^{13}C\ ^0/_{00}$ (error)	^{14}C age (y BP)	Calendric age range - 2σ	Calendric age range (probability)
GRA8/1	Charcoal of Ahb (*Rosmarinus officinallis)*	80-130	Poz-56539	-24.4 (0.3)	165 ± 25	1491-1658 Cal AD	1491-1602 Cal AD (0.704)
			Poz-56540	-25.2 (0.3)	180 ± 25	1658-1812 Cal AD	1727-1812 Cal AD (0.604)
GRA8/2	Charcoal of Ahb (bottom) (*Pistacia lentiscus*)	130-177	Poz-56541	-26.9 (0.5)	295 ± 30	1665-1814 Cal AD	1725-1787 Cal AD (0.444)
GRA2/1	2Ahb humus (upper)	100-120	Poz-59709	-27.2 (0.2)	1750 ± 30 *	224-384 Cal AD*	224-384 Cal AD* (1)
			Poz-59710	-26.1 (0.3)	1650 ± 30 **	264-532 Cal AD**	330-433 Cal AD** (0.896)
GRA8/2	Ahb humus (lower)	130-150	Poz-59707	-25.6 (0.4)	1725 ± 30 *	245-388 Cal AD*	245-388 Cal AD* (1)
			Poz-59708	-26.9 (0.2)	2095 ± 30 **	194-45 Cal BC**	194-45 Cal BC** (1)

4.5. Discussion

4.5.1. Terracing and soils

The overall morphological characteristics of these soils suggest the importance of the soil movement (earthworks) during terrace building, which was followed by the silting up of the terraces through the addition of new rows of stones (Fig. 4.9; Seguí, 2003) over an extended period of time- in most cases until the present day. Eroded upslope material was retained and integrated into the terrace soil profile very quickly, such material probably beging a pedosediment as shown by the rather high organic matter content of the paler uppermost Bw horizons. The predominance of slope and short-distance transport processes is evidenced by the absence of both fluvial materials and of high-energy deposits at the flat valley bottoms which lack talweg incisions. Nevertheless, external anthropic inputs (ceramics, charcoal, high amounts of phosphorous) seem to be scarce. Therefore, the darker, crumby Ahb horizons are interpreted as relict horizons whose present position can be partly explained by the earthworks that took place during terrace building. In this overall morphology we include the shapes, thicknesses and lateral continuity of these Ahb horizons in the study site as well in other places of Les Garrigues, and also the transitions of such Ahb horizons to underlying and overlying horizons.

One of the salient features of these Ahb horizons is the structure made by fauna which corresponds to the definition of the vermic qualifier (IUSS-WRB, 2006). Garrigó and Bech (1999) proposed the use of such qualifier in soils of the Prades mountain range, south of Les Garrigues, on dolomite rocks, under oak vegetation and a xeric moisture regime.

In order to qualify as a mollic horizons (SSS, 2010; IUSS-WRB, 2006), the buried horizons need to have a higher amount of organic carbon (more than 2.5%). Since their carbonate content is higher than 40 % the requirements for a dark value may be waived. Our interpretation is that their organic matter content was much higher at the moment of the burial, and afterwards the humus underwent decomposition (Stevenson, 1969), reducing the amount of organic matter and diminishing the colour value. The fact that in the current soil surveys of the area mollic horizons have never been mapped reinforces such idea: the Ahb horizons where buried at different depths at the time of terrace building, and they lost organic matter and colour, a process more pronounced at shallower depths.

We believe, with the available information, that most of the buried soils would have qualified for a Calcaric, Vermic Phaeozem (calcaric) (IUSS-WRB, 2006) at the time of burial. They were young soils with mollic horizons (Haploxerolls and Haplustolls (SSS, 2010), in our case) and lacking a calcic horizon. Phaeozems occur nearby the area in the foothills of Pre-Pyrenees at altitudes about 900 meters asl, moister climate, calcareous rocks and limestones, and under a degraded oak forest vegetation. They are extensive in the Mediterranean region (Jones *et al.,* 2005). In the NE Spain Haplustolls (more rainfall in summer) and Haploxerolls have been mapped in many places at 800-900 m asl under oak forest cover (Gómez-Miguel, 2006).

The overthickening of some of the Ahb horizons could be due to slope process, in addition to terracing works. We have often noted that the presence of Ahb horizons is prevalent in sloping infilled gullies, a favourable place for such accumulation. Morever, these overthickened Ahb horizons are almost absent in the major valley bottoms, where pedosediments seem to be dominant according to soil survey reports (Carrillo *et al.,* 1999; Boixadera *et al.,* 2012).

Figure 4.9. Stone wall close to profile GRA8 with the uppermost stone layer added after the building of the main part (Seguí, 2003)

Terracing helped preserve these soils since it stabilized the landscape from which the pedosediment originated. Lack of tool marks (such as spade imprints) in the soils from the earthworks suggest dry conditions during terrace building, which helped preserve the relict soil good structure. During the terracing, erosion increased locally, but most of the sediments were retained by the system. Original topsoils were also moved and thickened in some parts (landfills) where they were buried. Silt cappings and fragments of surface crusts, formed by turbulent flow due to terracing as well as passing through channels of dead tree roots, could date from that time.

The darker colours of the Ahb horizons can be neither explained by a higher SOM content nor a different texture. Eckmeier *et al.* (2007) attribute the dark colour of chernozems to black carbon, but this is probably not the cause in our case given the low amount of charcoal observed. A possible explanation for this difference may be that a different type of OM is present in the Ahb horizons, due to different vegetation and biological activity. Indeed, faunal structure and low bulk densities are very evident in these horizons and different from the present Ap horizons. Research in this direction could help solve this question.

Calcium carbonate redistribution in the “new” soils is very limited because of the short time span (450 years at most), in a dry, arid environment with highly calcareous materials. Micromorphological observations confirm this because pseudomycelia are formed by needle-shaped calcite -a transient form-, whereas queras are biogenic micro-redistributions of carbonates. Some of the queras are transformed to micrite. Similar processes were observed by Rabenhorst and Wilding (1986), West *et al.* (1988) and Manafi and Mahmoodi (2006) from needle fibre calcite. The latter authors suggested that given enough time, the growth pressure of the crystals is the cause of the micritisation of the acicular calcite coatings. In our case this is not the reason, since the pseudomorphs after cells are stable and do not grow further after the formation of the quera, therefore the explanation would be a simple reprecipitation in the mould voids.

More advanced stages of carbonate accumulation are not observed. The observed soil development in the Ahb horizons is in good agreement with current available information about other soils of the area. Badia *et al.* (2009) showed that significant calcium carbonate accumulation does not take place in geomorphic surfaces younger than 11 kyr (Lewis *et al.,* 2009). Althought Retallack (1994) prevents any straightforward interpretation of palaeosol data, the available information about present-day similar soils (IGC-DAAM-ICC, 2011) indicates a moister, milder climate in the past, compared with the present one in the study area. On the other hand, the absence of significant amounts of ceramics and the low P content excludes the anthropic origin of these Ahb horizons. The lack of Bwk horizons underlying the Ahb supports the idea of a pedosediment as the parent material of these soils and suggests a prior erosion period before the formation of the (now buried) A surface horizons at that time. The present soil morphology - Bw paler than Ahb horizons but organic-matter rich at the top of Ahb horizons - reveals the subsequent erosion after terracing, with the sediments having been retained in the terraces by addition of new rows of stones (Fig. 9).

Dating of terraces is a very difficult task, as Denevan (2001) pointed out. The aim of this work is focussed on the Ahb horizons rather than the terraces themselves; but we cannot overlook the abovementioned difficulties because of the existing relationship between the terracing process and the Ahb horizons. This prevents a straightforward interpretation of pollen data, because mixing of Ahb horizons by earthworks could have occurred, changing the chronological distribution of the materials at depth. Dating of charcoals obtained in GRA 8 (similar ages at different depths) reinforces this interpretation.

When studying buried horizons using humus radiocarbon ages, it is assumed that they become closed systems (Alexandrovskiy and Chichagova, 1998; Pustovoytov, 2006), because the input of organic matter is virtually stopped. Under these conditions of a well isolated buried horizon, it is concluded that humus radiocarbon ages of buried horizons could be considered as an approximate age of the burial (Alexandrovskiy and Chichagova, 1998; Pustovoytov, 2006). In Les Garrigues, available evidence seems to be that the former dark A horizons were buried by the generalised terracing during the 18th century. Field work also reveals that Ahb horizons where not isolated.

The ^{14}C ages of the humic acids for the two dated buried horizons are very similar (224-388 cal yr AD), and correspond to the late Roman period. The interpretation of humus dating is not easy, since the dated object (humus) is a mixture of organic matters with different ages, which can span a variable time length depending on the SOM turnover time for that particular soil (Scharpenseel and Becker-Heidmann, 1992; Chichagova, 2005; Eckmeier *et al.,* 2007). A source of inaccuracy is the existence of present or past calcium carbonate remobilisation through the profile, because CO_2 of lithogenic origin released by calcium carbonate precipitation can be bioassimilated and mask the isotopic signature of atmospheric carbon (Scharpenseel and Becker-Heidmann, 1992). This "hard-water effect" is known to occur on sediments and aquatic organisms surrounded by carbonate-rich rock, that yield sediment dates much older than their true age (Olsson, 1986). It is not likely to take place in our soils under this semi-arid climate. On the contrary, sediment contamination by younger carbon sources, as roots or bioturbation (McGlone and Wilmshurst, 1999) is more probable. The high faunal activity in these horizons, and perhaps turbulent flow evidenced from silt coatings (Fig. 4.6) may have had a rejuvenating influence into some humus fractions (Gerlach *et al.,* 2006). The mixing of materials during the building of the terraces in GRA8, with anomalous thickness, can also be the reason for this high variability.

Humus radiocarbon ages must be taken as minimum humus ages (Bluszcz *et al.,* 2007; Eckmeier *et al.,* 2007; Albrecht and Kühn, 2011), in such a way that sometimes these ages have been considered as the last input of organic material into the horizon (Albrecht and Kühn, 2011; Pietsch and Kühn, 2014). Eckmeier *et al.* (2007) obtained Holocene radiocarbon ages spreading over 3700 years, which were interpreted as mean residence times of SOM, and not as absolute ages (see also Hetier *et al.,* 1983). Likewise, we can interpret our radiocarbon BP (2050-1650 yr) ages also as turnover times, and expect that the formation period extended much longer that the calibrated ages, e.g. during ca. the last 4000 yr.

4.5.2. Palaeoclimatic implications of the biomorphic indicators

The combination of several soil survey techniques, pollen analyses, and other biomorphic indicators makes it possible to date major changes in the study of geo-ecological evolution (Van Mourik *et al.,* 2012). Overall, the results of the pollen analysis indicate that woody vegetation was dominant in the area during the time of formation of Ahb horizons. However, the upper levels of the three profiles show a process of forest clearance. This is evident in the overlying Bw horizons and can also be noticed in the upper levels of the Ahb horizons, and would have occurred during the time of construction of terraced systems. Pine and evergreen oak forests represent the main communities in the area. This wood composition corresponds to what is considered to be nowadays the climax vegetation, pointing to the fact that the bioclimatic conditions were broadly similar to the present ones. In addition, shrub taxa also correspond to Mediterranean-continental species now existing in the area as *Erica t. Juniperus, Arbutus unedo, Cistus* or *Rosmarinus t*.

The pollen assemblages of Ahb horizons of profiles GRA5 and GRA2 show the expansion of evergreen oak communities displacing secondary woody communities such as pines and scrubs. However, the profile GRA8 has a different pollen spectrum, because here the pine forests gradually change at the expense of the evergreen oak formation. These different behaviours could be due to material mixing during earthworks, a fact that is reinforced by forest clearances of the uppermost samples. Moreover, this profile probably underwent landfilling (large thickness of the buried horizon, location at the edge of a terrace), therefore this should be not taken as a trend, since the material deposition may not be chronological.

In most samples of Ahb horizons, the reduced values of herbaceous taxa that are indicators of disturbances and human impact activities, such as weeds, crops and nitrophilous taxa, show that the human activities are present only at regional scale and do not directly affect the study area.

During the formation of Bw horizons, besides the clearance activities, the increase of olive trees in the Bw horizons of GRA5 and GRA8 that reflect the expansion of olive cultivars is remarkable. The highest values of *V. vinifera* in the Bw horizon of GRA2, located at the valley bottom, indicate that vineyards could have occupied the terraces.

Pollen studies of a nearby plain (Alcarràs, 250 m. asl) indicate a predominance of pine and evergreen oak forest communities between 1400 and 800 cal yr BC, with the sporadic presence of deciduous trees, continental maquis and scrubs (Alonso *et al.,* 2002). In the closer Urgell plain and internal foothills of pre-coastal mountain ranges, the plant cover composed by forest communities of evergreen oaks and pines was remarkable towards 1400 cal yr BC (Alonso *et al.,* 2002). These authors characterized a closed canopy environment, similar to that reported in Ahb horizons from La Granadella, and this evidence suggests that these buried soils could have developed from the middle Holocene.

At the Ivars site (endorheic lake sediments), a similar evolutionary trend of the forest canopy to that observed in la Granadella occurred between the 2nd and 5th centuries AD (Currás, 2012). The pinewoods, predominant during the 2nd century AD suffered a quick regression from 3rd century AD, parallel to the expansion of evergreen oaks, a community that reached its maximum expansion in the 5th century AD, similar to that recorded in profiles GRA2 and GRA5. These changes are consistent with a weak human activity, in particular with a limited representation of crops. Only from the 6th century AD on, these communities of evergreen oaks started to be deforested due to a recurrence of fires and to an expansion of farming activities (Currás, 2012).

The higher precipitation periods reported by Voltas *et al.* (2008) in the region (1800–900 BC; 300 BC–300 AD) that alternated with drier periods (900–300 BC; 900 AD–present). Currás (2012) detected an aridification period (7th century AD) in Ivars lake pollen records. Moreover, Voltas *et al.* (2008) indicated that this higher rainfall would mostly correspond to an increase in summer precipitation, under which biomass production and organic matter dynamics would be different from today.

Phytolith records also support the pollen results in showing a vegetation consisting mainly of trees (*Quercus* and *Pinus)* in the Ahb horizons and grasses in the Bw3 horizon of profile GRA5, even though the main limitation for the interpretation is the low amount of phytoliths encountered. The formation of phytoliths in monocotyledonous plants, including grasses, sedges and palms, is notably higher than in dicotyledonous plants (Piperno, 1988, 2006; Albert and Weiner, 2001; Tsartsidou *et al.,* 2007). Recycling of silica by vegetation in different landscapes is also another factor for phytolith production (Bartoli, 1983; Meunier *et al.,* 1999). Nevertheless and despite this higher phytolith production there is a differential preservation of phytoliths, which depends on different causes such as the degree of silicification in the plant, which at the same time is reflected in the different morphological types. For example the characteristic hat-shaped sedge morphotype, although it is produced in huge numbers in the plants, does not preserve well in soils and disappears from the record soon after deposition. Other morphological types such as short cells from grasses remain in the soil but in lesser amounts (Albert *et al.,* 2006).

Solubility of silica is independent of pH below 9, and from that point increases sharply (Wilding *et al.,* 1977). In our highly calcareous, salt free soils with a pH below 8.5 we must conclude that phytolith dissolution due to high pH is not the cause for the low phytolith presence. Neither etched silica grains nor amorphous silica in the soil pores are observed in the micromorphological study. This interpretation is consistent with the identification of the multicellular polyhedral morphotypes from dicotyledonous leaves identified in the lowermost levels and which require stable chemical conditions in order to be preserved. Nevertheless, the low number of short cell morphotypes from grasses recovered from one of the uppermost levels, is not consistent with the high production of phytoliths, and of these morphotypes, in this family. Thus, keeping in mind that phytoliths become part of the soil after plant decomposition, their low presence in the studied samples needs to be related to other external factors such as the probable removal of vegetation, or surface erosion by runoff that would eliminate the phytoliths produced by plant decomposition.

Although a high percentage of charcoal fragments belonging to a shrub (*Rosmarinus officinalis*) are located in a single sample, the diversity of this taxonomic analysis indicates a vegetation type formed by the same number of species of shrubs and trees. As with other disciplines, charcoal analysis has limitations for landscape reconstruction. This is due to factors such as the possible selection of wood to be charred by the society of that time, or the different evolution of charred fragments with time, that alters the original plant distribution.

Charcoal identification is not contradictory with the pollen and phytolith records and its dating confirms that terrace building is in accordance with the historical records.

4.6. Conclusions

A combination of techniques was used for the first time in the study of buried Ahb horizons in a terraced area in the Ebro Valley that allowed us to elucidate some of the forming conditions of these soils. They were formed before the onset of the generalized farming activities in the area, as is proved by the prevalence of woody vegetation (pollen and phytoliths) from that time and is a plant configuration which is also shown in regional palaeoenvironmental records. The formation could have occurred over a long period of time under tree vegetation, probably under a moister climate.

The overall information from the biomorphic indicators, Ahb-charcoal ages and soil development is coherent with the hypothesis of terracing being responsible for the burial of the original Ah horizons. The very heterogeneous pattern of the soil cover as observed today is due to both the original soil cover, and the earthworks needed to conform the terracing.

Since we found that the buried horizons are a very characteristic feature of this terraced landscape, it can be suggested that it is used as a criterion in soil classification.

More information such as a higher number of surveys, biomorphic analyses and dating in more landscape units, as well as detailed organic matter characterisation (e.g. black carbon or lipid analyses) are needed in order to fully exploit the potential information of these Ahb horizons, in particular the degree of anthropic influence.

Acknowledgements

The authors thank the invaluable help of Carmen Herrero (DAAM, profile information), Asier Santana (SCT-UdL, making soil thin sections) and Dr. Michele Francis (U. Stellenbosch, language review) and two anonymous referees for their useful comments.

References

Adderley WP, Wilson CA, Simpson IA, Davidson DA. 2010. Anthropogenic features. *In*: Stoops G, Marcelino V, Mees F. (Eds.), Interpretation of micromorphological features of soils and regoliths. Elsevier. pp. 569-588.

Albert RM, Weiner S. 2001. Study of phytoliths in prehistoric ash layers using a quantitative approach, *In:* Coline JDMF. (Ed.), Phytoliths, Applications in Earth Sciences and Human History. A.A. Balkema Publishers, pp. 251-266.

Albert RM, Bamford MK, Cabanes, D. 2006. Taphonomy of phytoliths and macroplants in different soils from Olduvai Gorge (Tanzania) and the application to Plio-Pleistocene palaeoanthropological samples. *Quaternary International* **148**: 78-94.

Albert R, Esteve X, Portillo M, Rodríguez-Cintas A, Cabanes D, Esteban I, Hernández F. 2011. Phytolith CoRe, Phytolith Reference Collection. Downloaded September, 2012 May 04. Retrieved Nov 11, 14, from http://www.gepeg.org/enter_PCORE.html.

Albrecht C, Kühn P. 2011. Properties and formation of Black Soils on the Island of Poel (NE Germany). *Quaternary International* **243**(2): 305-312.

Alexandrovskiy AL, Chichagova OA. 1998. Radiocarbon age of Holocene paleosols of the east European forest–steppe zone. *Catena* **34**(1): 197-207.

Alonso N, Gené M, Junyent L, Lafuente A, López JB, Moya A, Tartera E. 2002. Recuperant el passat a la línia del Tren d'Alta Velocitat. L'assentament protohistòric, medieval i d'època moderna de El Vilot de Montagut (Alcarràs, Lleida). Pagès Editors, Lleida.

Asins-Velis S. 2006. Abandono de terrazas agrícolas: procesos de erosión y desorganización del paisaje, in: Actes de les Jornades sobre Terrasses i Prevenció de Riscos Naturals. Mallorca, September 2006. pp. 289-301.

Badia D, Martí C, Palacio E, Sancho C, Poch RM. 2009. Soil evolution over the Quaternary period in a semiarid climate (Segre river terraces, northeast Spain). *Catena* **77**: 165–174.

Bartoli F. 1983. The biogeochemical cycle of silicon in two temperate forest ecosystems. *Environmental Biogeochemistry Ecology Bulletin* **35**: 469-476.

Behre KE. 1981. The interpretation of anthropogenic indicators in pollen diagrams. *Pollen et Spores* **23**: 225-245.

Benyarku CA, Stoops G. 2005. Guidelines for preparation of rock and soil thin sections and polished sections. Quaderns DMACS, 33, Universitat de Lleida, Lleida.

Bluszcz A, Poręba GJ, Śnieszko Z. 2007. The basis of the study of the age of the Holocene diluvium on loess areas of Polish Highlands. *Geochronometria* **28**(1): 61-66.

Boixadera J. 1985. Two examples of physiographically related Calcic Cambisols from the Ebro Basin. MSc Thesis. Agric. Univ. Wageningen.

Boixadera J, Herrero C, Danes R, Roca J. 1989. Cartografía de suelos semiàridos de regadío: Área regable de los canales de Urgell (Lérida). XVI Reunión de la SECS. DMCS-UPC & SECS.

Boixadera J, Seguí P, Llop JM, Poch RM. 2012. Soils on Stone-Wall Bench Terraces in Les Garrigues. Mid-Meeting Excursion Guide. 14th Int. Working Meeting on Soil Micromorphology. Ed. Universitat de Lleida. Lleida.

Brock F, Higham T, Ditchfield P, Ramsey CB. 2010. Current pretreatment methods for AMS radiocarbon dating at the Oxford Radiocarbon Accelerator Unit (ORAU). *Radiocarbon* **52**(1): 103-112.

Bronger A, Catt JA. 1989. Paleosols: problems of definition, recognition and interpretation. *Catena Supplement* **16**: 1-7.

Carrillo G, Llop JM, Herrero C, Sió J, Boixadera J. 1998. Mapa de sòls detallat (1/25.000) del Garrigues sud. Bovera – La Granadella. DARP- Generalitat de Catalunya. Lleida. pp. 174.

Chichagova OA. 2005. Absolute and relative ages of soils from radiocarbon dating: development of IP Gerasimov's ideas. *Eurasian Soil Science* **38**(12): 1277-1285.

Currás A. 2012. Estudio sobre la evolución de paisajes mediterráneos continentales en Lleida y Guadalajara durante los últimos 3000 años a partir de las secuencias polínicas de Ivars, Somolinos y Cañanamares. PhD thesis. Universitat de Barcelona. Tesis Doctorals en Xarxa. http://www.tdx.cat/handle/10803/96089

Denevan WM. 2001. Cultivated landscapes of native Amazonia and the Andes. Oxford University Press, Oxford.

Donkin RA. 1979. Agricultural Terracing in the Aboriginal New World. Viking Fund Publications in Anthropology, **56**. Tucson, Arizona, pp. 196.

Eash NS, Sandor JA. 1995. Soil chronosequence and geomorphology in a semi-arid valley in the Andes of southern Peru. *Geoderma* **65**(1): 59-79.

Eckmeier E, Gerlach R, Gehrt E, Schmidt MW. 2007. Pedogenesis of Chernozems in Central Europe—a review. *Geoderma* **139**(3): 288-299.

Faegri K, Iversen J. 1989. Textbook of modern pollen analysis - 4th Ed. Wiley. Chichester.

FAO. 2006. Guidelines for profile description. 4th edition. FAO. Rome.

French CAI, Whitelaw TM. 1999. Soil erosion, agricultural terracing and site formation processes at Markiani, Amorgos, Greece: The micromorphological perspective. *Geoarchaeological: An International Journal* **14**(2): 151-189.

Garrigó J, Bech J. 1999. The vermic features in the xerept suborder. *In*: Bech J. (Ed.). 6th International Meeting on Soils with Mediterranean Type of Climate. Extended Abstracts. Barcelona. pp. 418-421.

Gerlach R, Baumewerd-Schmidt H, Van den Borg K, Eckmeier E, Schmidt MW. 2006. Prehistoric alteration of soil in the Lower Rhine Basin, Northwest Germany—archaeological, ^{14}C and geochemical evidence. *Geoderma* **136**(1): 38-50.

Goeury C, De Beaulieu JL. 1979. À propos de la concentration du pollen à l'aide de la liqueur de Thoulet dans les sédiments minéraux. *Polen et Spores* **21**: 239-251.

Golyeva A. 2001. Biomorphic analysis as a part of soil morphological investigations. *Catena* **43**: 217-230.

Gómez-Miguel V. 2006. Geología, Geomorfología y Edafología. Monografías del Atlas Nacional de España, Instituto Geográfico Nacional, Madrid.

Gutiérrez-Elorza M, Peña-Monné JL. 1998. Geomorphology and late Holocene climatic change in Northeastern Spain. *Geomorphology* **23**: 205-217.

Herrero J. 1991. Morfología y génesis de suelos sobre yesos. Monografía INIA 77. Madrid.

Hetier JM, Guillet B, Brousse R, Delibrajs G, Maury RC. 1983. ^{14}C dating of buried soils in the volcanic Chaine des Puys (France). *Bulletin Volcanologique* **46**: 193-201.

Holliday VT. (Ed.) 2004. Soils in archaeological research. Oxford University Press, New York.

IGC – DAAM - ICC. 2011. Mapa geològic de Catalunya. Geotreball IV. Mapa de sòls. Les Borges Blanques, full 389-1-2 (65-30), 1:25 000.

IUSS Working Group-WRB. 2006. World reference base for soil resources 2006. A framework for international classification, correlation and communication. World Soil Resources Report 103. FAO. Rome.

Jones A, Montanarella L, Jones R. 2005. Soil atlas of Europe. European Commission. Brussels.

Jorda M, Vaudour J. 1980. Sols, morphogènese et actions anthropiques à l'époque historique s.I sur les rives nord de la méditerranée. Naturalia Monspeliensia, hors Serie. Colloque de la Fondation L. Emberger sur "La mise en place, l'évolution et la caracterisation de la flore et de la végetation circunméditerranéenne". Montpellier. pp. 173-184.

Julià R, Marquès MA. 1983. Geologia. *In*: Porta J, Julià R. (Eds.). Els sòls de Catalunya: Àrea Meridional de Lleida". Departament d'Agricultura, Ramaderia i Pesca de la Generalitat de Catalunya. Barcelona. pp. 49-67.

Katz O, Cabanes D, Weiner S, Maeir AM, Boaretto E, Shahack-Gross R. 2010. Rapid phytolith extraction for analysis of phytolith concentrations and assemblages during an excavation an application at Tell es-Safi/Gath, Israel. *Journal of Archaeological Science* **37**: 1557–1563.

Keeley HCM. 1985. Soils of Prehispanic Terrace Systems in the Cusichaca Valley, Peru. *In*: Farrington IA. (Ed.), Prehistoric Intensive Agriculture in the Tropics. British Archaeological Reports International Series 232. Oxford, vol. 2, pp. 547–568.

Lewis CJ, McDonald EV, Sancho C, Peña JL, Rhodes EJ. 2009. Climatic implications of correlated Upper Pleistocene glacial and fluvial deposits on the Cinca and Gállego Rivers (NE Spain) based on OSL dating and soil stratigraphy. *Global and Planetary Change* **67**: 141-152.

Madella M, Alexandre A, Ball TB. 2005. International Code for phytolith Nomenclature 1.0. *Annals of Botany* **96**: 253-260.

Manafi Sh, Mahmoodi Sh, 2006. Micromorphology of secondary calcium carbonate accumulations in some soils around Urmia Lake. *Iranian Journal of Agricultural Science* **26**: 1399-1411. (In Persian).

Martín F, Serra R. 1991. Les construccions de pedra seca a la comarca de les Garrigues. Pagès Editors. Lleida.

McClung de Tapia E, Solleiro-Rebolledo E, Gama-Castro J, Villalpando JL, Sedov S. 2003. Paleosols in the Teotihuacan valley, Mexico: evidence for paleoenvironment and human impact. *Revista Mexicana de Ciencias Geológicas* **20**(3): 270-282.

McGlone MS, Wilmshurst JM. 1999. Dating initial Maori environmental impact in New Zealand. *Quaternary International* **59**(1): 5-16.

Meunier JD, Colin F, Alarcon C. 1999. Biogenic silica storage in soils. *Geology* **27**: 835-838.

Mulholland SC, Rapp Jr G. 1992. A morphological classification of grass silica-bodies. *In:* Rapp JrG., Mulholland SC. (Eds.), Phytolith Systematics, Emerging Issues, Advances in Archaeological and Museum Science. Plenum Press, New York, pp. 65-89.

Olsson IU. 1986. A study of errors in 14C dates of peat and sediment. *Radiocarbon* **28**: 429-435.

Pietsch D, Kühn P. 2014. Buried soils in the context of geoarchaeological research—two examples from Germany and Ethiopia. *Archaeological and Anthropological Sciences* 1-13.

Piperno DR. 1988. Phytolith Analysis. An Archaeological and Geological Perspective. Academic Press, San Diego, California.

Piperno DR. 2006. Phytoliths: A comprehensive guide for archaeologists and paleoecologists. AltaMira Press, Lanham.

Piqué R. 2006. Los carbones y las maderas de contextos arqueológicos y el paleoambiente. *Ecosistemas* **15** (1): 31-38.

Porta J, Herrero J. 1983. Els sòls. *In*: Porta, J., Julià, R. (Eds.), Els sòls de Catalunya: Àrea Meridional de Lleida. Departament d'Agricultura, Ramaderia i Pesca de la Generalitat de Catalunya. Barcelona. pp. 69-307.

Porta J, López-Acevedo M, Rodríguez R. 1986. Técnicas y experimentos en Edafología. Col·legi Oficial d'Enginyers Agrònoms de Catalunya, Barcelona.

Pustovoytov K. 2006. Soils and soil sediments at Goebekli Tepe, southeastern Turkey: a preliminary report. *Geoarchaeology* **21**(7): 699-719.

Rabenhorst MC, Wilding LP. 1986. Pedogenesis on the Edwards Plateau, Texas: III. New Model for the Formation of Petrocalcic Horizons. *Soil Science Society of America Journal* **50**: 693-699.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, HattŽ C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. 2013. IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years cal BP. *Radiocarbon* **55**(4): 1869-1887.

Retallack GJ. 1994. The environmental factor approach to the interpretation of paleosols. *Soil Science Society of America Journal Special Publication* **33**:31-64.

Ruhe RV. 1956. Geomorphic surfaces and the nature of soils. *Soil Science* **82**: 441-455.

Sandor JA, Eash NS. 1995. Ancient agricultural soils in the Andes of Southern Peru. *Soil Science Society of America Journal* 59: 170-179.

Sandor JA. 2006. Ancient agricultural terraces and soils. *In*: Warkentin BP. (Ed.), Footprints in the Soil: People and Ideas in Soil History, Elsevier, Amsterdam, pp. 505-534.

Scharpenseel HW, Becker-Heidmann P. 1992. Twenty-five years of radiocarbon dating soils: paradigm of erring and learning. *Radiocarbon* **34**(3): 541-549.

Schweingruber FH. 1991. Anatomie Europäischer Holzer-Anatomy of European woods. Haupt, Bern und Stuttgart: Eidgenössische Forschungsanstalt für Wald, Schee und Landschaft, Birsmendorf (Hrsg). Haupt, Bern und Stuttgart.

Scudder SJ, Foss JE, Collins ME. 1996. Soil science and archaeology. *Advances in Agronomy* **57**: 1-76.

Seguí P. 2003. Los suelos de los bancales de piedra seca en Cataluña: morfología y aproximación taxonómica. Engineering Thesis. Escola Tècnica Superior d'Enginyeria Agrària-Universitat de Lleida.

Spencer JE, Hale JA. 1961. The origin, nature and distribution of agricultural terracing, Pacific Viewpoint 2, 1-40.

SSS - Soil Survey Staff. 2010. Keys to Soil Taxonomy, 11th ed. USDA-NRCS, Washington, DC.

Stevenson FJ. 1969. Pedohumus: accumulation and diagenesis during the Quaternary. *Soil Science* **107**: 470-479.

Stoops G. 2003. Guidelines for analysis and description of soil and regolith thin sections. Soil Science Society of America Inc., Madison. Wisconsin.

Tsartsidou G, Lev-Yadun S, Albert RM, Miller-Rosen A, Efstratiou N, Weiner S. 2007. The phytolith archaeological record: strengths and weaknesses based on a quantitative modern reference collection from Greece. *Journal of Archaeological Science* **34**(8): 1262-1275.

Twiss PC, Suess E, Smith RM. 1969. Morphological classification of grass phytoliths. *Soil Science Society of America Proceedings* **33**(1): 109-115.

Van Mourik JM, Seijmonsbergen AC, Jansen B. 2012. Geochronology of Soils and Landforms in Cultural Landscapes on Aeolian Sandy Substrates, Based on Radiocarbon and Optically Stimulated Luminescence Dating (Weert, SE-Netherlands). *In*: Michalska Nawrocka D. (Ed.), Radiometric Dating, InTech., pp. 75-114.

Vita-Finzi C. 1969. The Mediterranean Valleys: Geological Changes in Historical Times. London: Cambridge University Press. New York, pp. 140.

Voltas J, Ferrio JP, Alonso N, Araus JL. 2008. Stable carbon isotopes in archaeobotanical remains and palaeoclimate. *Contributions to Science* **4**(1): 21-31.

West LT, Wilding LP, Hallmark CT. 1988. Calciustolls in central Texas: Genesis of calcic and petrocalcic horizons. *Soil Science Society of America Journal* **52**: 1731-1740.

Wilding LP, Smeck NE, Drees LR. 1977. Silica in soils: quartz, cristobalite, tridymite, and opal. *In*: Dixon JB, Weed SB. (Eds.). Minerals in Soil Environments. Soil Science Society of America, Madison, Wisconsin, pp. 471–552.

Yaalon DH. 1971. Soil-forming processes in time and space. *In*: Yaalon DH. (Ed.). Paleopedology. Origin, nature and dating of paleosols. International Society of Soil Science and Israel University Press, Jerusalem.

CAPÍTOL 5:

Anthropogenic soils from Llanos de Moxos (Bolivia): soils from Pre-columbian raised fields (*camellones*)

Article submitted:

Boixadera, J., Esteban, I., Albert, R.M., Poch, R.M. 201X. Anthropogenic soils from Llanos de Moxos (Bolivia): soils from pre-columbian raised fields (*camellones*). *Journal of Quaternary Science*

ANTHROPOGENIC SOILS FROM LLANOS DE MOXOS (BOLIVIA): SOILS FROM PRE-COLUMBIAN RAISED FIELDS (*CAMELLONES*)

Jaume Boixadera[1,2*]; Irene Esteban[3]; Rosa M. Albert[3,4];Rosa M. Poch[1]
[1]Dept. Medi Ambient i Ciències del Sòl, U. de Lleida.
[2]Dept. Agricultura, Ramaderia, Pesca i Alimentació, Generalitat de Catalunya.
[3]ERAAUB. Dept. de Prehistòria, Història Antiga i Arqueologia. Universitat de Barcelona.
[4] ICREA Research Professor.
[*]corresponding author: jaume.boix@macs.udl.cat

Abstract

Raised field cultivation (c*amellones*) is a Pre-Columbian technique, now abandoned, which is very extensive in the Llanos de Moxos (Bolivia) specially in the San Ignacio de Moxos sector. The objectives of the research were to find out the main properties of the natural and non-cultivated soils of the area and to understand the effects of human actions on the morphology, genesis and characteristics of soils on ridged fields and also their past use. We studied several soils (transect Trinidad-San Borja; natural and anthropogenic soils around San Ignacio and also five representative raised field soils.

The natural soils are acidic, show a wide range of clay contents and the most common feature is their hydromorphism (Boixadera *et al.,* 2003), showing different degrees of human action according to their phosphorus content. The soils of the raised fields show a distinct pattern of redoximorphic features from ridge to channel, as well as pH and aluminum saturation; they do not have artifacts or charcoal, and their color and P content is similar to that of surrounding soils. Phytoliths from maize have been found in them .Soil-forming processes are very active and are related to fine fraction mobility and redoximorphic features.

The raised fields were probably built to improve the drainage conditions. Chemical soil fertility was not the main issue and they were used for cultivation including maize. The set of characters encountered may be used for the classification of the raised field soils.

Key words: Soil fertility, maize cultivation, redoximorphic features, soil classification, soil micromorphology.

Supplementy material related to this article found, after references

5.1. Introduction

After the seminal work of Sombroek (1966) there has been increasing evidence of the extensive influence of humans on the soils of the one-time thought to be pristine Amazonian Basin environment. The best known of these human-influenced soils are the so called "*terra preta do indio*" or indian dark earths, a dark-coloured anthropic epipedon, usually rich in nutrients (Lima *et al.,* 2002). These soils are found in the Amazonia basin mounds (*lomas*) of different sizes, up to 60 ha or more. These dark earths (ADE) have merited a lot of attention and among their main characteristics are: high C content, dark color, high P content and charcoal (*biochar*) (Woods and Glaser, 2004; Kämpf *et al.,* 2003). Other anthropogenic soils in Amazonia are the "*tierras castañas*" a lighter coloured variant of the indian dark earth, which has not been very much studied (Woods and McCaan 1999).

Much less attention has been paid to the raised fields (*camellones*), a kind of ridge and bed fields with channels between them. These techniques of cultivation or reclamation of lowlands are well spread all over the world: chinampas and raised fields (*camellones*) are systems of wetland cultivation in America. Deep soils constructed of organic-rich lacustrine sediments, forming a system of artificial channels and islands (chinampas) exist in Central Mexico.

The overall extent of the *camellones* remains largely unknown. They are mentioned by many authors in all Amazonia from Bolivia to Santarem (Denevan, 2006); other places where they occur are in the Orinoco headwaters (Colombia), Venezuela (Zucchi and Denevan, 1979) and in the Andes (Ecuador), especially in Tiwanako (Erickson, 1996).

Very extensive Pre-Columbian earthworks exist in the Llanos de Moxos (Bolivia): mounds (*lomas*), raised fields (*camellones*), causeways (*terraplenes*), channels and ditches (Erickson, 1995), the most striking ones being the so-called "*camellones*" (large beds). Nordenskiöld (1924) was the first to note their presence and later Plafker (1963) but especially Denevan (1974) gave full accounts of them, providing an overview of their presence in Amazonia. Denevan (1974) also gave information on quotations about raised fields in the chronicles of the first Spaniards. According to Erickson (1995), raised fields were built in the seasonally inundated savannahs. They are found under herbaceous vegetation but also under forest, although the latter remain largely unknown. They have been dated from 300 BC to 1400 AD (Erickson, 1995) using several techniques, especially radiocarbon. Since the first notice appeared of the raised fields (*camellones*) in Bolivian Amazonia a large amount of information has been produced, especially in the fields of archaeology and the social sciences.

Erickson was the first to study them in a systematic way (Erickson *et al.,* 1994) from an archeological point of view and a significant amount of information has been produced (Erickson, 2003; Walker, 2008; Lombardo *et al.,* 2011a) ,but little information is available from the pedological point of view (Walker, 1997 ;Wilson 2002). Usually raised fields have very few remnants of artifacts, pottery or even charcoal; some authors claim that the "*camellones"* were part of an agricultural system which was almost fire free (Lombardo *et al.,* 2011b) but many of these as been questioned (Prúmers, 2007). It has been claimed that many agricultural techniques were used in the raised fields, such as irrigation, drainage and fertilization, (Erickson, 1995; Barba *et al.,* 2003) but these points remain speculative in most of cases. It is now well established and accepted that maize and mandioca (cassava) were part of the agricultural system of the raised fields (Whitney *et al.,* 2014; Villalba *et al.,* 2004).

Natural soils, soils under current slash and burn agriculture (*chacos*) as well as other soils with clear anthropogenic marks were studied in the San Ignacio region (Llanos de Moxos, Bolivia). The objective of our research was to find out the main characteristics and soil forming processes acting in the natural and human altered soils and especially in the soils of the raised fields. The main aim was to understand the effects of human action on the morphology, properties, nutrient contents, water dynamics and soil forming processes of these soils and also their past land use. The results on the natural soils are reported elsewhere (Boixadera *et al.,* 2003). In this paper we report on the effects of human intervention in the morphology, properties, nutrients and water dynamics of the ridged field soils.

5.2. Physical setting

The Llanos de Moxos (LM; Fig. 5.1) is a vast plain (≈200,000 km^2) in the middle of the Madeira catchment, at the foot of the Andes (130-200 m a.s.l.). It is filled with Tertiary and Quaternary sediments, but only the latter outcrop. The LM forms one of the largest wetlands of the world. They are located in the middle reaches of the Mamoré river, before Caechuela Esperanza. They are drained by several rivers from the Andes, which join together into the Madeira river, one of the largest tributaries of the Amazon.

The slope is (Guyot, 1993) very low(less than 10 cm/km) and the hard rocks area of Caechuela Esperanza and the uplift of the Brazilian Shield (Plotzki *et al.,* 2011) prevents a quick down cutting of the rivers. The area is flooded yearly to an extent between 8,000 to 100,000 km^2

depending of the rainfall (Lombardo, 2010), strongly influenced by the natural oscillation of *El Niño*. Flooding comes from the Andes rivers, but also from local rainfall and the effect of backwater. It may reach from decimeters to several meters according to the geomorphological position. The plain is crossed by the Mamoré and Beni rivers, both of them of the white waters type. Many rivers from the plains have their headwaters in the Andes, but others drain only inner parts of the LM. The rivers from the Andes carry large amounts of sediment, estimated $65 \cdot 10^9$ T/year, from which 60% are deposited in the LM (Guyot, 1993). In addition to the sediments a considerable amount of dissolved materials are also present in the waters. Rivers from the Andes carry large amounts of sediments, therefore avulsion and changes in the river courses are quite common (Lombardo, 2010). They have built up levees, oxbow-lakes, abandoned meanders and similar forms, evidence of a very intensive fluvial activity (Lombardo *et al.,* 2012). Rectangular lakes are found very often; some authors have argued they have an anthropic origin (Belmonte and Barba 2011) but the idea of a natural origin seems to prevail (Hinkel, 2006; Gonzales and Aydin, 2008). Present levees, paleolevees, rectangular lakes and many other landforms are easily seen, but an overall geomorphological view is still lacking.

The rainfall in LM ranges from 1200 to 2000 mm/year (Plotzki *et al.,* 2011), with a dry season from March to June Strong winds from the south (*surazo*) are a particular climatic feature.

Vegetation is dominated by herbaceous plants in the lowlands (savannah) and forest extends in high lying areas (rainforest, some islands being attributed to human activity). Local people know very well the hydrological behavior and vegetation of each area (e.g. *monte lavadero*, *monte alto*, *monte bajo*). Large areas are currently devoted to cattle ranching, using fire to create pastures. Agriculture is also practiced in the form of slash and burn (*chacos*).

Several studies exist on the soil of the region (Haase, 1992; Hannagart, 1993; Boixadera *et al.,* 2003). From them, the emerging picture of the soil cover pattern is Oxisols in the north (Baures), and Entisols, Alfisols and Ultisols in the South.

Soil texture vary according to the geomorphological position. They go from very sandy near the Mamoré river to heavy clay in the basins. Soils in the San Ignacio area are supposed to be the most fertile in LM (Lombardo *et al.,* 2013). East of the Maniquí River, as well as in the region of Pantanal and in Paraguay soils with a significant content of sodium have been described.

Erickson (1995) claimed that more than 100,000 ha of raised beds exist, but this is highly uncertain because parts of them are under forest and hardly visible. The ridges are 20-40 cm high and the raised fields are 4-6 meters wide in many cases. Most likely they have not been used for agricultural production since their abandonment before the arrival of the Spaniards. Some of them are badly eroded by grazing animals and in most cases the furrows or channels have accumulated sediment and organic matter.

The studied area around San Ignacio de Moxos belongs to what Lombardo *et al.* (2013) has called the "raised fields area" in opposition to the "mounds area", East of Trinidad and the "monumental area" in the North.

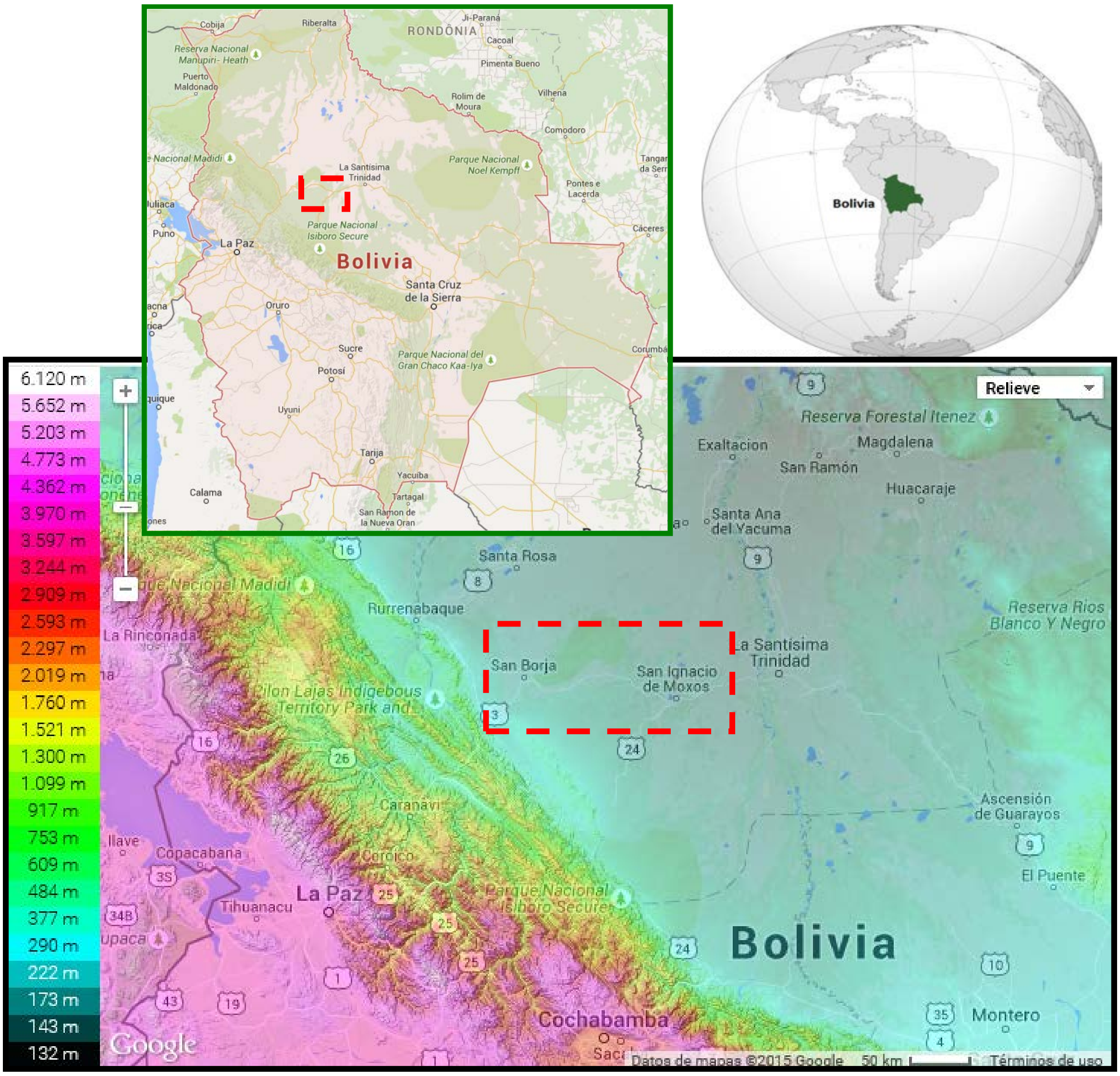

Figure 5.1. The San Ignacio de Moxos area (Google maps, 2015)

5.3. Material and methods

5.3.1. Field studies

Selected profiles from natural soils of the area were studied (results reported in Boixadera *et al*., 2003) and also a W-E transect of about 220 km from the banks of Mamoré river (Trinidad) to Maniquí river (San Borja) In that transect, observations (auger holes) were made in the main landforms. Also, as part of that basic survey, slash and burn (*chacos*) fields and other earthworks (mounds, causeways) were sampled along the years 1997-1999.

In the area a large number of earthworks were present and visited during the survey. Five raised bed field were studied (Table 5.1). All of them are typical "*camellones*"; MOX-99-3 as a different morphology and likely its functions were anothers. Trenches were opened in MOX-6, MOX-51, MOX 99-3 and MOX 99-8 from raised part (ridge) to the furrow (channel) (Figs. 5.2 and 5.5). Data from natural soils, near the raised fields, were opened (MOX-3 for MOX-6; MOX-55 for MOX-51; MOX-26 for MOX-99-3).

Table 5.1. Main site and geometry of studied raised fields (*camellones*)

Site	Geomorphogical position	Vegetation / land use	Ridge		Actual height difference ridge/channel cm	Reworked soil material	
			Length m	Width m		Ridge cm	Channel cm
La Vibora (MOX-6)	Basin	*Pampa*; herbaceous pasture	> 200	2.1	40	33	25/43
Estancia San Pedro (MOX-24)	Basin; near a *curiche*	*Pampa*; herbaceous pastures	-	4.0	50	-	-
Moxitania 1 (MOX-51)	Former levee	Forest (*monte alto no chaqueado*)	85	5.0	36	53	34
Estancia San Pedro (MOX-99-3)	Levee	Forest (*monte lavadero*)	200	3.0	150	40-80 (210 ceramics)	-
Moxitania 2 (MOX-99-8)	Basin	*Pampa*; herbaceous pastures	90	5.0	30	46	20

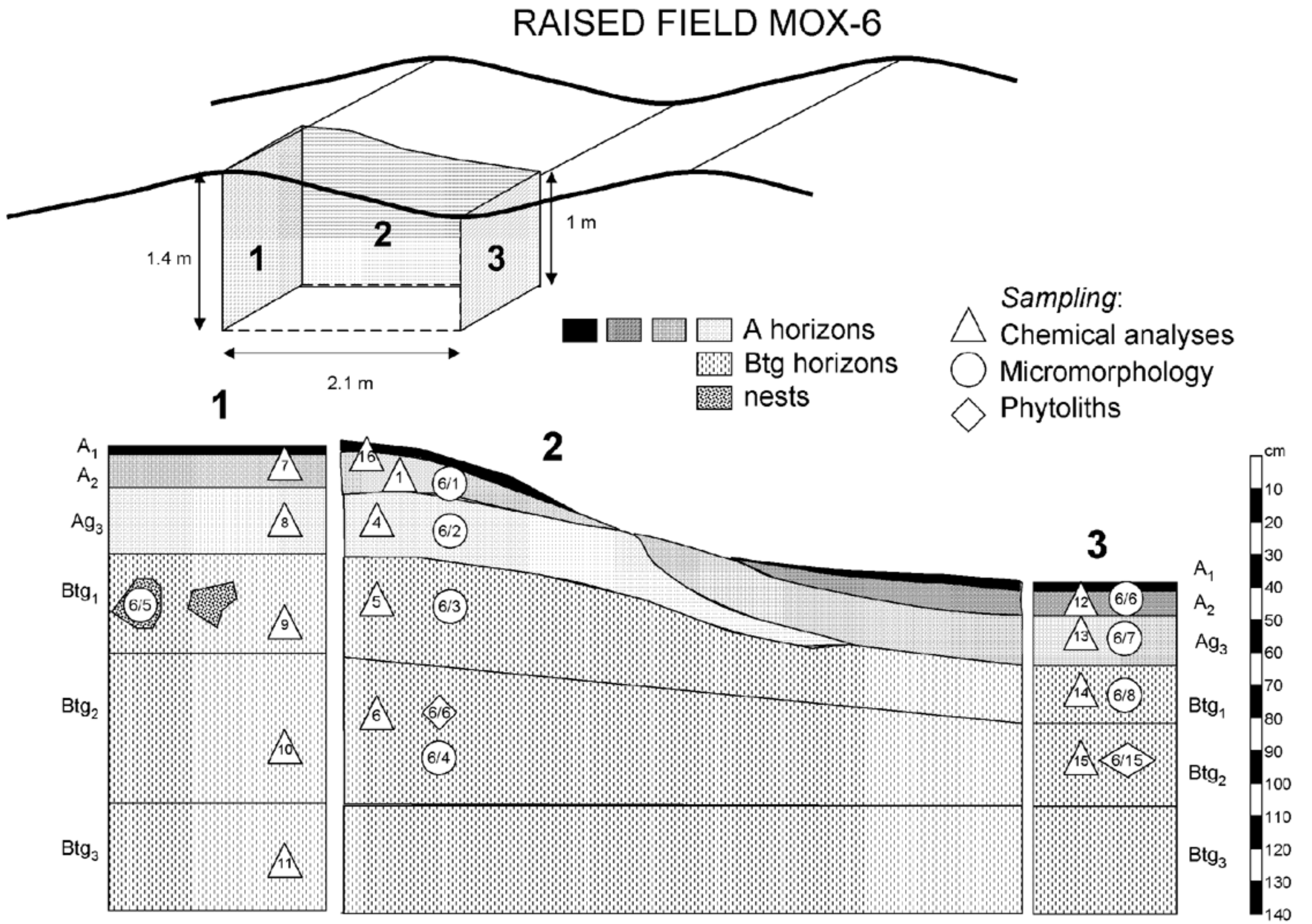

Figure 5.2. Genetic horizon of raised field MOX-6 (La Vibora). Sampling studies for chemical analysis, micromorphology and phytolits

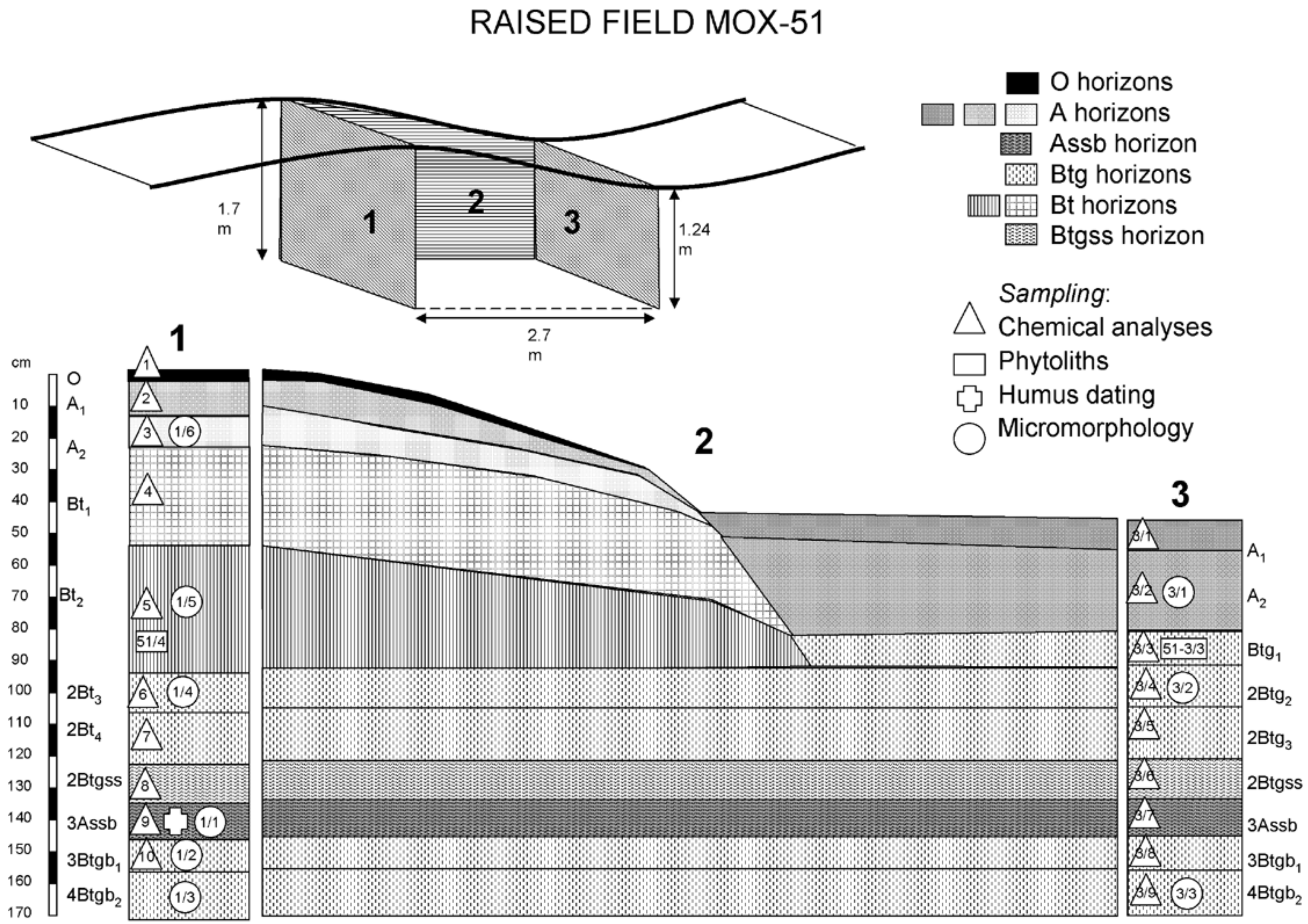

Figure 5.3. Genetic horizon of raised field MOX-51. Sampling studies for chemical analyses, phytoliths, humus dating, and micromorphology

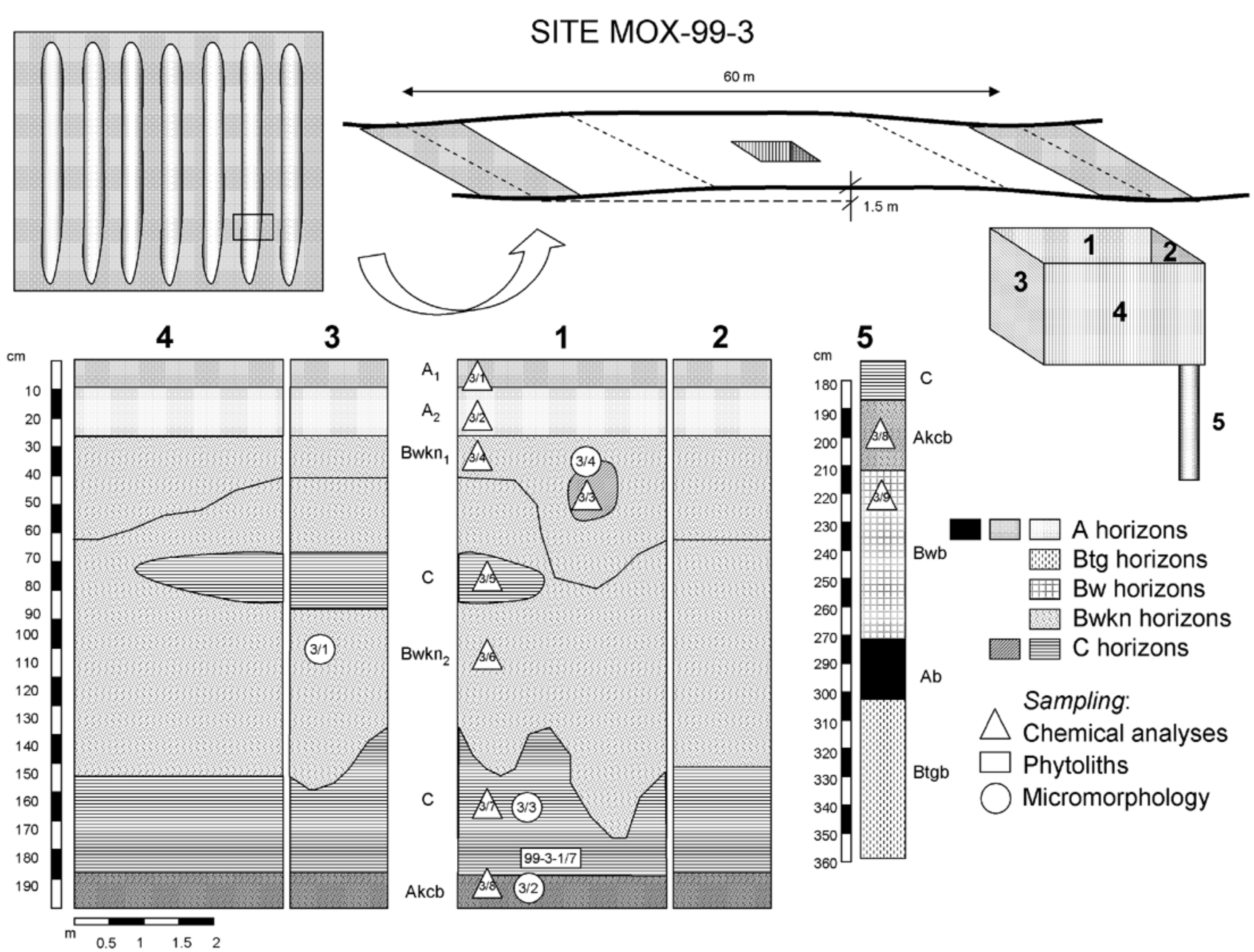

Figure 5.4. Genetic horizon of raised field MOX-93-3. Sampling studies for chemical analyses, phytoliths, and micromorphology

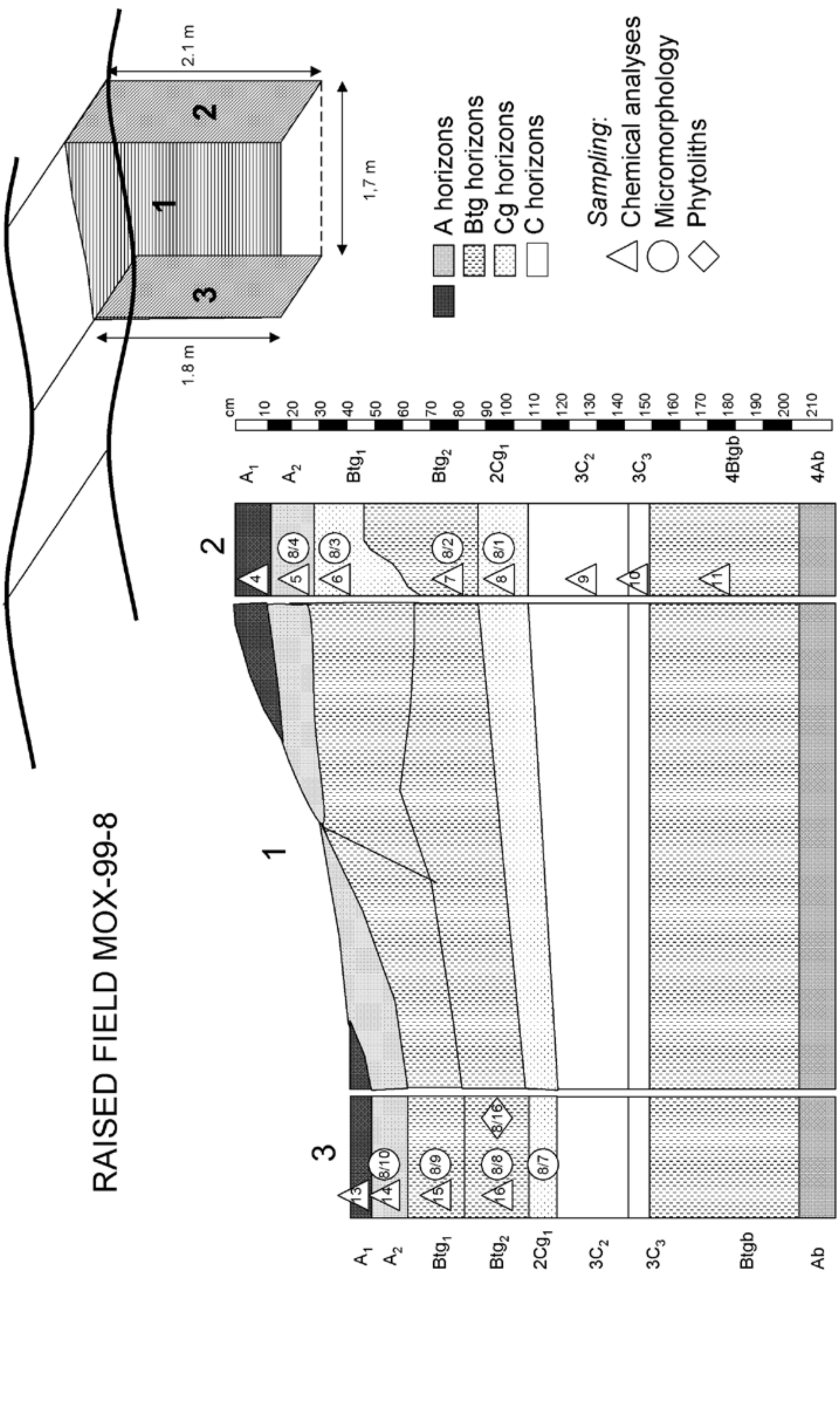

Figure 5.5. Genetic horizon of raised field MOX-99-8. Sampling studies for chemical analyses, micromorphology and phytoliths

In the estancia la Víbora a large raised field was studied. The ridges are near the Mausa Lake, where a mound and a ditch exist. They are badly eroded due to cattle grazing (Fig. 5.2). MOX-6 was excavated 160 m from the ditch surrounding the raised field.

The raised field of estancia San Pedro (Fatima) (MOX-24) is close to a mound and surrounded by a ditch and goes to a *curiche*. The soils were sampled by auger.

The raised fields sampled at estancia Moxitania (MOX-51 and MOX-99-8) come from a large area of raised fields. They are under forest (MOX-51) and savannah (MOX-99/8) (Figs 5.2 and 5.5).

MOX-99/3 is in estancia San Pedro and is located in a set of a non-typical raised fields. They are part of 3 large raised fields near a small *arroyo* (gully) and are never flooded (Fig. 5.4).

5.3.2. Description of profiles and soil sampling

Profiles were described following SINEDARES (CBDSA, 1983). Samples were taken for physico-chemical analysis. Undisturbed samples were collected at selected profiles and horizons for micromorphological (25x15x15 cm), and phytolith analysis.

5.3.3. Physico-chemical analysis

The physico-chemical analyses of the soils were done according to Porta *et al*. (1996), MAPA (1996) and Page *et al.* (1982). Particle size distribution was determined by pipette method, following organic matter removal with H_2O_2 and dispersion with Na-hexametaphosphate. Organic matter content was obtained through wet oxidation (Walkley-Black method). Total nitrogen and extractable phosphorus were determined following Kjeldahl and Olsen methods respectively. Calcium carbonate was determined with the Bernard calcimeter. Cation exchange capacity (CEC) was determined with 1M NH4OAc (pH 7), exchange cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) were measured by atomic absorption after they were extracted by 1M NH_4OAc. Extractable aluminum was measured after extraction by KCl 1M. Base saturation (V, %) was calculated by sum of exchange bases divided by CEC. ECEC was computed as the sum of exchangeable Al^{3+}, Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}. Aluminum saturation was computed as the extractable Al divided by ECEC (Fageria and Baligar 2003). CEC-ECEC was calculated because it is considered an indicator of variable charge (Summer and Noble, 2003).

5.3.4. Micromorphological analysis

Undisturbed soil samples were collected at selected profiles and horizons. Vertical thin sections, 13cm long and 5.5 cm wide were made following the procedures described in Benyarku and Stoops (2005) and were the studied using a polarizing microscope, according to the guidelines of Stoops (2003). We followed Lindbo *et al.* (2010) to describe the redoximorphic features.

To assess the type and degree of hydromophism we follow the approach proposed by Lindbo *et al.* (2010).

5.3.5. Phytolith analysis

Table 5.2 summarizes the main site characteristics of studied phytolith samples. Selected samples were analysed for phytoliths following the extraction procedure described in Katz *et al.* (2010). Phytoliths were counted in 20 random fields at 200 × and 400 × magnification. Morphological identification was based on our modern plant reference collection (Albert *et al.,* 2011) on standard literature (Mulholland and Rapp, 1992; Piperno, 1988, 2006; Twiss *et al.,* 1969) and the phytolith studies conducted on plants and soils from Neotropics (e.g. Piperno, 1984; Piperno and Pearsall, 1993; Piperno and Pearsall, 1998; Iriarte, 2003; Pearsall *et al.,* 2003; Piperno, 2009; Dickau *et al.,* 2013). The International Code for Phytolith Nomenclature was also followed where possible (Madella *et al.,* 2005).

5.3.6. Humus dating

A humus sample from a buried horizon of MOX-51 was selected for radiocarbon dating. The methods of chemical pretreatment were those used in the Oxford Radiocarbon Accelerator Unit, as described by Brock *et al*. (2010). 14C ages were calibrated with CalPal library (2003-2007).

Table 5.2. Main site and soil characteristics of studied phytolith samples

Site	Reference	Genetic horizon	Depth cm	*Camellon* position	pH	Remarks
Estancia La Vibora (MOX-6)	MOX-6/6	Btg_2	63-108	ridge	6.6	Same *camellon* and genetic horitzon
	MOX-6/15	Btg_2	43-68	channel	5.9	
Estancia Moxitania 1 (MOX-51)	MOX 51/4	Bt_2	53-92	ridge	6.2	Same *camellon*, but different genetic horitzon
	MOX 51-3/3	Btg_1	34-46	channel	5.7	
Estancia San Pedro (MOX-99-3)	MOX99-3-1/7	C	150-180	ridge	9.3	*Terraplén*
Estancia Moxitania 2 (MOX-99-8)	MOX99-8/16	Btg_2	40-53	channel	5.3	No equivalent at ridge

pH: relation 1 soil: 2.5 distilled water

5.4. Results

5.4.1. General properties of the soils of the area

The soils of the San Ignacio de Moxos area are slightly acid (Summer and Noble*,* 2003), both in the topsoil and subsoil, higher than 4.3 in the most acidic ones (Table 5.3), but milder pHs are dominant, making them suitable in many cases for crop growth from the soil chemical point of view. They are moderate to slightly acid in scale proposed by Summer and Noble (2003).

Table 5.3. Summary characteristics of soils from San Ignacio de Moxos area

Surface horizons 0-20 cm	pH	P Olsen mg/kg	O.C %	Clay %	n	Sites
Soils of the slash and burn plots (*chacos*)	5.6 (4.6-7.6)	12.8 (3.8-33.2)	1.6 (0.5-4.0)	13.6 (8.8-19.8)	12	8
Soils of the mounds (*lomas*)	6.9	59.6 (5-162)	1.1 (0.1-1.8)	20.1 (12.1-33.0)	7	6
***Camellon* soils (Raised fields)**	5.1 (4.7-5.6)	8.8 (1-23)	2.0 (0.6-4.5)	27.9 (18.9-41.0)	17	5
Forest soils	5.1 (4.4-5.9)	12.5 (7-30)	2.3 (0.7-5.6)	37.9 (10.9-67.0)	8	7
Savanna soils (*pampa*)	5.5 (4.3-7.3)	7.8 (1.8-12)	2.4 (0.8-5.8)	44.9 (16.5-71.9)	20	12

pH: relation 1soil: 2.5distilled water; P: phosphorus by Olsen method; O.C.: organic carbon; n: number samples studied. Values in parenthesis are range

Subsurface horizons 20-120 cm	pH	P Olsen mg/kg	O.C %	Clay %	n	Sites
Soils of the slash and burn plots (*chacos*)	5.6 (4.3-7.4)	5.2 (3.2-8.5)	x	15.9 (9.1-20)	8	8
Soils of the mounds (*lomas*)	7.1 (5.6-8.3)	62.5 (28-145)	0.4 (0.1-0.7)	20.9 (6.8-27.8)	12	6
***Camellon* soils (Raised fields)**	6.2 (5.1-7.7)	4.4 (1.3-11.1)	x	28.2 (13.2-46.5)	22	5
Forest soils	5.5 (4.7-6.2)	13.9 (6-28)	x	26.5 (2.5-81.9)	19	6
Savanna soils (*pampa*)	6.1 (4.5-8.2)	3 (0.5-9)	x	45.1 (17.9-83.4)	37	11

pH: relation 1soil: 2.5distilled water; P: phosphorus by Olsen method; O.C.: organic carbon; n: number samples studied .Values in parenthesis are range; x: no value

The forest soils have a higher pH overall (Table 5.3) than savannah soils if we exclude the saline spots found. In any case in all soils the pH never is below 4.3, with the average being 5.5 or more. CEC ranges from 10 to 32 cmol+/kg and base saturation is almost always higher than 50% (Tables S5.1, S.5.2, S.5.3; Boixadera *et al.,* 2003). Aluminum saturation is low, with the higher figure around 40% (Table S5.2).

Most of the chemical characteristics of the soils are quite similar between the different vegetation/land uses if we exclude the soils of the mounds (Table 5.3). Among them we must point out that slash and burn and raised field soils exclude the most clayey soils. Organic matter is lower in mounds and in slash and burn soils as a result of the cultivation practices. We must conclude, with the data available, that most of the soils of our mounds are not dark earths. The general properties of the raised field soils do not differ from those of the other not drastically disturbed soils.

Phosphorus content is quite similar in all cases (7.8-12.8 mg/kg average) and it may be slightly higher in the slash and burn soils. The phosphorus content of the studied soils (Table S5.1) is also high in some places, a fact that might demonstrate human activities, although they may not be easily noticed from the surface soil morphology. It should be kept in mind that P Olsen gives only a general idea of P content, and its results are dependent of the degree of waterlogging (Patrick *et al*., 1985), although it may help to identify areas of part intensive land use.

The soils of the transect Mamoré-San Borja shows a good relationship soils-landforms. Soil drainage differences are clearly associated to present vegetation. Soil texture also shows a general relationship with landforms but in these cases it should be considered the alluvial nature of these soils, with the intensive dynamics of the river system (Plozki et al., 2011; Lombardo *et al.,* 2015b); soils with as high as 94% clay may be found under forest. The soils retain its fluventic character (more than 0.2 OC at 125cm; SSS, 2014).

The present soil distribution is better understood if we consider the pattern of flooding and sediments transport. Mamoré river, but also Maniqui and Apere river (Guyot, 1993) are white water rivers carring water and sediments from the Andes and flooding a significant area, where they deposite a large part (60%; Guyot, 1993) of their sediments, but the extension is limited according to Plozki *et al.* (2013). The rest of the area, specially between Mamoré river and San Ignacio, is an area where flooding is due to backwater and low permeability soils; many streems (Tinamuchi river; Cuberena river) drain the area reworking the sediments form the plain. Levees are found in very high clay soils.

In the not clearly disturbed soils of the area, Boixadera *et al.* (2003) reported a dominant 2:1 clay mineralogy, with illite dominant (usually > 40%), smectite second (>15%) and kaolinite third (usually < 15%.) with chlorite in some cases, very different from the kaolinite dominated assemblages characteristic of more weathered environments likely from the northern part of *Llanos de Moxos* (Hanagarth, 1993; Lombardo *et al.,* 2015a). The redoximorphic features as a result of the yearly waterlogging are prominent in the soils with Fe reduction being a very active process with a stagnic pattern in most cases (Boixadera *et al.,* 2003). Other main soil forming processes are argilloturbation and bioturbation while ferrolysis is not evident. Very deep calcium carbonate accumulation is present in some soils as well as saline spots (*salitrales*).

5.4.2. Soils of the raised fields

Site characteristics

The present height between the bottom of the channel and the top of the ridge is 0.40 m in MOX-6, 0.36 m in MOX-51 and 0.30 m in MOX-99/8 (Table S.5.1). The raised fields of La Vibora (MOX-6) are currently eroding due to cattle overgrazing. The other raised fields seem not to be eroded as yet.

From the study of the ridge/channel horizons the lack of any plan when disposing the materials to construct the ridges seems apparent, with no clear intention to preserve the topsoil fertility (nutrients and organic carbon).

Raised fields from Estancia Moxitania (MOX-51 and MOX-99/8) are part of a complex of earthworks (mounds, ditches and raised fields) reported by Juan-Tresserras *et al.* (2005) and Villalba *et al.* (2004). In a mound close to MOX-51, Juan-Tresserras *et al. (*2005) dated ceramic materials with thermoluminiscence (TL) from a burial at 1075±156 years BP (VIII to XI A.D). Other TL dating from mounds close to our study area and reported by the same authors yield similar age results (X to XII A.D). Moxitania mound does not show the characteristics of Amazonian dark earths. We assume the earthwork complete is form these age.

MOX-99/3 presents a very much different morphology and characteristics. Its geometry is very different of typical raised fields (Denevan, 1970), as well as its geomorphic position (now neven flooded). It seems to be a different type of earthwork and perhaps had another function. The material shows macroscopically "*hojaldre*" structures (Herrero *et al.,* 1989), typical of sodic environments. Its chemical characteristics (slightly saline at depth, strongly alkaline, sodic: ESP>25%) makes it not very suitable for crop growth although many plants semi-tolerant to exchangeable sodium may be grown (Ayers and Westcot, 1985).

The geomorphic positions (basins and levees) and land uses (grazed savannah and forest) illustrate the diversity of places where raised fields are found.

Soil macromorphological characteristics

Soil color, organic carbon and redoximorphic features are different in the ridges and the channels of the raised fields (Table 5.4A to 5.4D). Topsoil has chroma less than 4, usually 2 or less; hue is 7.5YR to 10YR and value 3 to 6. The subsoil color in the savannah raised fields has a hue of 2.5Y (La Víbora) or 10YR (Moxitania) and 7.5YR or even 5YR in the forest raised fields. Organic matter usually accumulates in the channel.

Redoximorphic features are shown by low matrix hues (2.5Y, La Víbora) and by mottling with different colors between the ped faces and inside the peds; and by Fe-Mn concretions. The ridges show less redoximorphic features, attesting better drainage conditions.

Clay (and silt) illuvation is also an ubiquitous feature. It is present in all profiles, both in the likely not perturbed subsoils, as well as in the voids of the topsoil ridges and channels.

We identify Bt horizons in all the materials. In the savannah (poorly drained) sites they are Btg throughout (low chroma and/or strong mottling). The horizon shows clear boundaries among them.

Several profiles have buried A and Bt horizon at different depths (MOX-51; MOX-99/3; MOX-99/8). Some of them show slickenside, likely to presence of smectite.

Charcoal and artifacts are absent. An exception is MOX-99/3 where ceramics and bones are present to a significant extent. MOX-99/3 has a different geometry, physicochemical characteristics and although it has been included in the raised field group of observations, its use could have been slightly different. MOX-99/3 is a soil with three tiers (Table 5.4C) (two buried soils, two Calciustept and the other a Ustalf) and it shows calcium carbonate accumulations, a high bioturbation, macromorphological infillings of fauna holes and cavities in the form of fine layered sediments (*hojaldre*) and has alkaline conditions.

Table 5.4A. Morphological properties of the raised fields. *Estancia* la Vibora: MOX-6

Side/ position	Genetic horizon	Depth cm	Munsell colour (moist.)	Soil structure	Mottling		Artifacts/ charcoal
					Amount	Colour	
Side 2	A_1	0-5	10 YR 3.5/2	granular	few	10 YR 7/6	charcoal
Ridge;	A_2	5-13	10 YR 3/2	sab	many	7.5 YR 4/6	charcoal
close to the top	Ag_3	13-33	10 YR 4/2	sab	many	7.5 YR 2.5/6	-
of the camellon	Btg_1	33-63	2.5 Y 7/1(surface peds) 2.5 YR 3.5/6(inside peds)	large prisms; blocks	many	2.5 Y 6/1 2.3 Y 8/4	-
	Btg_2	63-108	2.5 Y 8/1(face peds) 5 YR 5/6(inside peds) 2.5 Y 7/4 (inside peds) 2.5 Y 7/1 (inside peds)	large peds; blocks	-	-	-
	Btg_3	108-140	2.5 Y 7/1(ped faces) 2.5 Y 4/6 (inside peds) 10 YR 7/4 (inside peds)	large prims; blocky -	-	-	-
Side 3	A_1	2-10	10 YR 3/2	sab	few	10 Y 3/1	charcoal/bones
Channel	A_2	10-25	10 YR 3/2	large peds	common	5 YR 4/6	charcoal
	Btg_1	25-43	10 YR 3/2	large peds	common	5 YR 4/6	-
	Btg_2	43-68	2.5 Y 8/1(face peds) 5 YR 5/6 (inside peds) 2.5 Y 7/4 (inside peds) 2.5 Y 7/1 (inside peds)	-	-	-	-
	Btg_3	68-108	2.5 Y 7/1(face peds) 2.5 Y 4/6 (inside peds) 10 YR 7/4 (inside peds)	-	-	-	-

sab: subangular blocky

Table 5.4B. Morphological properties of the raised fields. *Estancia* Moxitania: MOX-51

Side/ position	Horizon genetic	Depth cm	Munsell colour (moist.)	Soil structure	Mottling		Artifacts/ charcoal	Remarks*
					Amount	Colour		
Side 2	O	0-2	-	-	-	-	no	-
Ridge	A_1	2-11	10 YR 5/4	sab	no	-	no	gradual horizon boundary
	A_2	11-22	7.5 YR 6/4	sab	no	-	no	-
	Bt_1	22-53	7.5 YR 4/4	sab	few	-	no	Fe, Mn, pisolits, clay coatings
	Bt_2	53-92	5 YR 5/4	granular	few	10 YR 1.7/1 10 YR 6/5	no	Fe, Mn, pisolits, clay coatings
	$2Bt_3$	92-106	5 YR 4/6	blocky	few	10 YR 1.7/1 10 YR 6/5	no	Fe, Mn, pisolits, clay coatings
	$2Bt_4$	106-123	5 YR 5/4	-	very few	10 YR 1.7/1	no	Fe, Mn, pisolits , clay coatings
	2Btgss	123-134	7.5 YR 6/2	blocky	few	10 YR 3/6 2.5 Y 7/6	no	Fe, Mn, pisolits, slickensides
	3Assb	134-146	5 YR 2/1	blocky	few	10 YR 1.7/1	charcoal	Fe, Mn, pisolits, slickensides
	3Btb	146-179	7.5 YR 5/6	sab	few	10 YR 1.7/1	charcoal	clay coatings
Side 3	A_1	0-10	2.5 Y 4/2	granular	no		no	-
Channel	A_2	10-34	10 YR 6/2	sab	few	10 YR 7/6	no	-
	Btg_1	34-46	7.5 YR 6/2	sab	few	7.5 YR 7/6 7.5 YR 2/1	no	-
	$2Btg_2$	46-54	5 YR 6/3	sab	few	7.5 YR 7/6 7.5 YR 2/1	no	Fe, Mn, pisolits

sab: subangular blocky
*Clear horizon boundaries

Table 5.4C. Morphological properties of the studied site. *Estancia* San Pedro: MOX-99/3

Side/ position	Horizon genetic	Depth cm	Munsell colour (moist.)	Soil structure	Mottling		Artifacts/ charcoal	Remarks
					Amount	Colour		
Side 1	0-10	A_1	10 YR 4/4	granular	no	-		
	10-27	A_2	10 YR 4/6	sab	no	-	no	
	27-42	$Bwkn_1$	10 YR 5/4	sab	no	-	ceramics and bones	$CaCO_3$ rhizoconcretions
	30-60	C	7.5 YR 5/5	*hojaldre*	few	-	-	
	71-89	C	7.5 YR 5/5	structureless	common	7.5 YR 5/2	-	$CaCO_3$ rhizoconcretions
	80-150	$Bwkn_2$	7.5 YR 5/5		few	-	ceramics	
	150-187	C	7.5 YR 5/5	structureless	few	-	-	
	187-210	Abknb	7.5 YR 5/4	sab	common	7.5 YR 5/6	ceramics	$CaCO_3$, and Fe, Mn, rhizoconcretions
	210-220	Bwknb	7.5 YR 5/6	sab	very many	-	-	*hojaldre* (some)
	220-230	Bwknb	7.5 YR 5/3	-	very many	-	-	*hojaldre* (some)
	230-240	Bwknb	7.5 YR 5/4	-	-	-	-	*hojaldre* (some)
	250-270	Bwknb	7.5 YR 5/2	-	-	-	-	*hojaldre* (some)
	270-300	Ab	7.5 YR 1/2	-	-	-	-	*hojaldre* (some)
	300-360	Btgb	5B 7/8	-	-	10 R 3/6	-	red mottles

sab: subangular blocky

Table 5.4D. Morphological properties of the raised fields. *Estancia* Moxitania: MOX-99/8

Side/ position	Horizon genetic	Depth cm	Munsell colour (moist.)	Soil structure	Mottling		Artifacts/ charcoal	Remarks*
					Amount	Colour		
Side 2 Ridge	A_1	0-11	10 YR 6/2	granular	no	-	no	-
	A_2	11-27	10 YR 6/1	sab	common	7.5 YR 6/6	no	-
	Btg_1	27-46/64	10 YR 8/1 (outside peds) 2.5 YR 6/8 (inside peds)	prismatic	-	-	no	clay coating in channels, Fe
	Btg_2	46/64-85	10 YR 8/2	-	very many	10 R	no	clay coating in channels
	$2Cg_1$	85-102	10 YR 8/2	-	common	10 R	no	-
	$3C_2$	102-137	10 YR 8/6	-	few	-	no	Fe, Mn, rhizoconcretions
	$3C_3$	137-144	7.5 YR 7/2	-	-	-	no	-
	4Btgb	144-197	7.5 YR 7/6	-	-	10 YR 8/1	no	Fe, Mn, rhizoconcretions
	4Ab	197-210	-	-	-	-	charcoal	-
Side 3 Channel	A_1	0-7	10 YR 6/1	granular	-	-	no	-
	A_2	7-20	10 YR 6/1	sab	-	-	no	-
	Btg_1	20-40	10 YR 7/1 (outside peds) 7.5 YR 5/6 (inside peds)	prismatic	many	7.5 YR 5/6	no	faunal infillings
	Btg_2	40-63	-	prismatic	few	7.5 YR 5/8	no	few coatings

sab: subangular blocky
* Clear horizon boundaries

Physicochemical conditions

All the raised fields were built in loamy, sandy loamy, sandy clay loamy soils or even finer materials. In the subsoil (Table 5.5A to 5.5D) clay may be as high as 45%, but silt is always the dominant fraction. In these textures capillary rise is significant.

Some properties - pH and organic carbon - are different in the ridge compared with the channel (Table 5.5A to 5.5D). The channel usually has a lower pH than the ridge; this may be due to the higher leaching of cations in the channel be explained by anthropogenic activity or buried horizon.

Organic carbon and phosphorus do not allows to detect to additional buried horizon. Organic carbon is higher in the channels than in the ridges but this may also be explained by the erosion of the ridges.

MOX-99/3 has a rather high P content (20-30 mg P/kg) throughout the profile, down to 210 cm, that almost doubles the content of the topsoil P (Table 5.5D). It can only be explained as a result of anthropogenic activities. In the raised fields the P content falls in the range of the studied soils (Table 5.3), although some odd results occurs some of them may.

All the rraised fields are non-saline, but site MOX-99/3 is a salt affected soil. Salinity is low (Table 5.5D) but sodicity is high (ESP: 26) as well as alkalinity (pH 9.2 to 9.7).

Cation exchange capacity (Tables 5.5A, 5.5B, 5.5C, 5.5Dbis) in the topsoils ranges from 8 to 17 cmol(+)/kg and in the subsoil from 8 to 21 cmol(+)/kg. Calcium dominates the CEC, but in some profiles (MOX-24, MOX-51) magnesium may be higher in some horizons. Base saturation is higher in the subsoil (43 to 100%) than in the topsoil A horizons (22 to 84%), and again is lower in the channels than in the ridges. Effective CEC (ECEC) is 4.7 to 14 cmol(+)/kg in the topsoil A horizons and from 7-14 cmol(+)/kg in the underlying horizons. Aluminum saturation never exceeds 50% and topsoil figures are higher than subsoil ones. Again aluminum saturation is lower in the channels than in the ridges. Variable charge (CEC-ECEC) is higher in the A horizons than in the underlying ones indicating that it is mainly due to the organic matter rather than to the clay minerals.

Table 5.5A. Main physicochemical properties of the raised fields studied. *Estancia* la Vibora: MOX-6

Side/ position	Reference	Genetic horizon	Depth (cm)	pH (1/2.5)	EC1/5 (dSm^{-1}. 25ºC)	Text. Class USDA	Sand	Silt	Clay	O.C %	P Olsen mg/kg
							----	%	----		
Side 1 Ridge	6-7	A_2	1-13	5.3	0.06	L	32.6	46.1	21.3	2.1	5
	6-8	Ag_3	13-33	5.6	0.06	L	30.3	45.9	23.7	0.8	3
	6-9	Btg_1	33-63	6.6	0.06	L	39.5	34.9	25.5	0.3	2
	6-10	Btg^2	63-108	6.9	0.06	CL	23.2	47.3	29.5	0.2	5
	6-11	Btg_3	108-140	7.2	0.06	L	39.2	41.4	19.5	-	5
Side2 Near the top of the ridge	6-16	A_1	0-5	5.1	0.06	L	31.8	46.1	22.1	4.5	23
	6-1	A_2	5-13	5.0	0.16	CL	23.8	43.3	32.8	2.0	10
	6-4	Ag_3	13-33	5.7	0.06	L	30.2	44.6	25.2	0.5	3
	6-5	Btg_2	33-63	6.1	0.04	L	37.0	40.9	21.8	0.2	5
	6-6	Btg_3	63-108	6.6	0.06	L	46.0	34.5	19.5	0.1	3
Side 3 Channel	6-12	A_2	2-10	4.8	0.19	CL	24.2	42.5	33.3	4.2	22
	6-13	Ag_3	10-25	4.7	0.09	CL	25.5	45.9	28.6	1.3	19
	6-14	Btg_1	25-43	5.2	0.06	CL	25.4	44.3	30.3	0.5	8
	6-15	Btg_2	43-68	5.9	0.05	CL	23.2	45.8	30.9	0.3	3

pH: relation 1soil: 2.5distilled water; EC: electrical conductivity relation 1soil/5distilled water; Textural classes: L: loam; CL: clay loam; Size limits of USDA, diameter in mm: sand (2.0-0.05); silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; P: phosphorus by Olsen method.

Table 5.5Abis. Main physicochemical properties of the raised fields studied. *Estancia* la Vibora: MOX-6

Side/ position	Reference	Genetic horizon	Depth cm	CEC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Al^{3+}	ECEC	CEC-ECEC	V %	∑Cat/ECEC	Al^{3+}/ECEC
				cmol +/kg										
Side 1	6-7	A_2	1-13	14.9	2.3	0.92	0.17	0.20	0.90	4.49	10.41	24.1	0.80	0.20
Ridge	6-8	Ag_3	13-33	15.2	1.9	1.17	0.28	0.10	1.36	4.81	10.39	22.7	0.72	0.28
	6-9	Btg_1	33-63	10.5	4.1	3.24	0.45	0.18	0.28	8.25	2.25	75.9	0.97	0.03
	6-10	Btg_2	63-108	15.0	8.6	4.90	0.90	0.29	0.06	14.69	0.31	97.9	1.00	0.00
	6-11	Btg_3	108-140	8.8	5.2	3.09	0.59	0.18	0.06	9.11	-0.31	103.0	1.03	0.01
Side2	6-16	A_1	0-5	8.1	2.4	0.50	0.65	0.16	1.62	5.33	2.77	45.8	0.70	0.30
Near the top	6-1	A_1	5-13	15.3	6.3	1.52	0.11	0.64	0.52	9.10	6.2	56.0	0.94	0.06
of the ridge	6-4	A_2	13-33	8.3	1.8	1.17	0.23	0.09	1.48	4.77	3.53	39.6	0.69	0.31
	6-5	Btg_1	33-63	10.0	4.1	2.33	0.29	0.17	0.93	7.82	2.18	68.9	0.88	0.12
	6-6	Btg_2	63-108	9.5	4.2	2.98	0.44	0.19	0.06	7.86	1.64	82.2	0.99	0.01
Side 3	6-12	A_2	2-10	17.4	4.5	1.67	0.11	0.54	0.24	7.07	10.33	39.2	0.97	0.04
Channel	6-13	Ag_3	10-25	12.8	3.5	1.71	0.12	0.18	1.15	6.66	6.14	43.0	0.83	0.17
	6-14	Btg_1	25-43	13.1	3.7	2.10	0.22	0.17	1.99	8.18	4.92-	47.3	0.76	0.24
	6-15	Btg_2	43-68	12.8	4.1	2.30	0.29	0.17	0.93	7.79	5.01	53.6	0.88	0.12

CEC: capacity exchange cation; Ca^{2+}: calcium; Mg^{2+}: magnesium; Na^{+}: sodium; K^{+}: potassium; Al^{3+}: Aluminum; ECEC: effective cation exchange capacity; V: base saturation; ∑Cat.: sum of cations

Table 5.5B. Main physicochemical properties of the raised fields studied: *Estancia* San Pedro: MOX -24

Side/ position	Reference	Depth cm	pH (1/2.5)	EC1/5 (dSm^{-1}. 25ºC)	Text. Class USDA	Sand	Silt	Clay	O.C %	N %	C/N	P Olsen mg/kg
							%					
Ridge	24-2	2-12	4.9	0.09	CL	29.4	37.3	33.3	4.1	0.34	12.1	89
	24-3	12-25	5.6	0.04	C	19.8	34.9	45.5	0.9	0.09	10.9	1
	24-4	35-45	6.2	0.05	C	21.0	37.8	41.2	0.4	0.07	5.6	n.d
	24-5	45-60	6.2	0.04	C	20.9	34.8	44.3	0.7	-	-	1
	24-6	60-75	6.7	0.04	L	51.2	30.6	18.1	0.1	-	-	6
	24-7	>75	6.6	0.05	CL	30.1	38.6	31.2	0.2	-	-	1
Channel	25-2	16-28	4.9	0.26	SiC	8.2	50.8	41.0	11.9	1.03	11.5	20
	25-3	28-38	5.0	0.08	-	-	-	-	4.0	0.42	9.6	6
	25-4	38-58	5.1	0.07	CL	29.6	40.2	30.2	-	-	-	-
	25-5	58-100	5.3	0.05	CL	29.7	40.7	29.6	-	-	-	-

pH: relation 1soil: 2.5distilled water; EC: electrical conductivity relation 1soil/5distilled water; Textural classes: CL: clay loam; C: clay; L: loam; SiC: silty clay; Size limits of USDA, diameter in mm: sand (2.0-0.05); silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; N: total nitrogen by Kjeldahl method; C/N; ratio total carbon/total nitrogen; P: phosphorus by Olsen method; n.d: not detectable.

Table 5.5Bbis. Cation exchange characteristics of the raised fields studied. *Estancia* San Pedro: MOX-24

Side/ position	Reference	Depth cm	CEC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Al^{3+}	ECEC	CEC-ECEC	V %	$\sum$Cat/ECEC	Al^{3+}/ECEC
				cmol + /kg									
Ridge	24/2	2-12	17.4	4.7	2.8	0.10	0.38	0.86	8.84	8.56	45.9	0.90	0.09
	24/3	12-25	15.8	6.3	6.6	0.09	0.37	0.56	13.92	1.88	84.6	0.96	0.14
	24/3	35-45	17.3	7.2	8.9	0.10	0.36	0.00	16.56	0.74	95.7	1.00	0.00
	24/4	45-60	19.2	7.6	9.6	0.12	0.39	0.00	17.71	1.49	92.2	1.00	0.00
	24/5	60-75	8.3	3.3	4.7	0.06	0.15	0.00	8.21	0.09	98.9	1.00	0.00
	24/6	>75	13.8	5.1	7.2	0.14	0.25	0.00	12.69	1.11	92.0	1.00	0.00

CEC: capacity exchange cation; Ca^{2+}: calcium; Mg^{2+}: magnesium; Na^{+}: sodium; K^{+}: potassium; Al^{3+}: Aluminum; Al^{3+}: Aluminum; ECEC: effective cation exchange capacity; V: base saturation. $\sum$Cat.: sum of cations

Table 5.5C . Main physicochemical properties of the raised fields studied. *Estancia* Moxitania: MOX-51

Side/ position	Reference	Genetic horizon	Depth cm	pH (1/2.5)	EC1/5 (dSm^{-1}. 25ºC)	Text. Class USDA	Sand	Silt	Clay	O.C. %	P Olsen mg/kg
							-------------- % ---------				
Side 1 Ridge	51/1	O	0-2	6.0	0.69	SiL	30.5	50.9	18.6	6.2	77
	51/2	A_1	2-11	5.0	0.60	SiL	27.9	54.2	17.9	4.0	47
	51/3	A_2	11-22	4.7	0.17	SiL	28.8	54.4	16.8	0.8	7
	51/4	Bt_1	22-53	6.2	0.07	SiL	27.9	53.2	18.9	0.3	3
	51/5	Bt_2	53-92	6.3	0.13	SiL	16.9	56.1	26.2	0.3	4
	51/6	$2Bt_3$	92-106	6.9	0.12	SiL	10.3	66.6	23.1	0.3	9
	51/7	$2Bt_4$	106-123	7.7	0.15	SiCL	5.6	60.8	33.6	0.3	11
	51/8	2Btgss	123-134	7.6	0.13	C	4.2	33.8	62.0	0.3	9
	51/9	3Assb	134-146	7.6	0.25	C	4.0	33.8	62.2	0.5	4
	51/10	3Btb	146-156	7.9	0.20	SiCL	9.7	51.5	38.8	0.3	24
Side 3 Channel	51-3/1	A_1	0-10	5.1	0.30	SiL	18.8	58.4	22.8	2.5	17
	51-3/2	A_2	10-34	5.3	0.05	SiCL	15.3	54.7	30.0	0.5	8
	51-3/3	Btg_1	34-46	5.7	0.04	SiCL	9.6	56.5	33.9	0.4	7
	51-3/4	$2Btg_2$	46-54	5.9	0.07	SiCL	9.8	62.6	27.6	-	5
	51-3/5	$2Btg_3$	54-70	5.0	0.08	SiCL	6.0	56.4	37.6	0.3	4
	51-3/6	2Btgss	70-83	6.2	0.10	SiC	5.4	48.4	46.5	0.4	4
	51-3/7	3Assb	83-97	-	-	-	-	-	-	-	-
	51-3/8	$3Btgb_1$	97-117	7.0	0.09	CL	23.6	47.5	28.9	0.3	11
	51-3/9	$4Btgb_2$	117-147	7.3	0.08	L	37.3	42.5	20.2	0.2	13

pH: relation 1soil: 2.5distilled water; EC: electrical conductivity relation 1soil/5distilled water; Textural classes: SiCL: silty clay loam; SiL: silt loam; SiC: silty clay; CL: clay loam; SCL: sandy clay loam; C: clay; L: loam; Size limits of USDA, diameter in mm: sand (2.0-0.05); silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; N: total nitrogen by Kjeldahl method; C/N; ratio total carbon/total nitrogen; P: phosphorus by method Olsen method

Table 5.5C bis. Cation exchange characteristics of the raised fields studied. *Estancia* Moxitania: MOX-51

Side/ position	Reference	Genetic horizon	Depth cm	CEC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Al^{3+}	ECEC	CEC-ECEC	V %	∑Cat/ECEC	Al^{3+}/ECEC
				cmol +/kg										
Side 1	51/1	O	0-2	21.6	12.65	7.98	0.21	0.96	-	-	-	100.9	-	-
Ridge	51/2	A_1	2-11	14.5	6.25	3.92	0.16	0.52	0.60	11.45	3.05	74.8	0.95	0.05
	51/3	A_2	11-22	7.8	3.05	1.30	<0.07	<0.03	0.55	5.00	2.80	57.1	0.89	0.11
	51/5	Bt_1	53-92	11.8	6.89	2.58	0.80	0.11	0.25	10.63	1.17	88.0	0.98	0.02
	51/6	$2Bt_2$	92-106	16.1	5.69	4.18	1.35	0.08	0.25	11.55	4.55	70.2	0.98	0.02
	51/7	$2Bt_3$	106-123	17.8	7.52	5.39	1.95	0.11	0.20	15.17	2.63	84.1	0.99	0.01
Side 3	51-3/1	A_1	0-10	13.5	6.73	2.20	0.10	0.22	0.25	9.50	4.00	68.5	0.97	0.03
Channel	51-3/2	A_2	10-34	12.3	4.76	2.28	0.28	0.15	1.55	9.02	3.28	60.7	0.83	0.17
	51-3/4	Btg_2	46-54	14.0	5.77	3.23	0.56	0.15	0.50	10.21	3.79	69.4	0.95	0.05
	51-3/5	Btg_3	54-70	14.6	6.09	5.49	1.00	0.16	0.95	13.69	0.91	87.3	0.93	0.07
	51-3/6	Btgs	70-83	21.1	7.52	9.29	1.41	0.20	0.24	18.66	2.44	87.3	0.99	0.01
	51-3/8	$3Btgb_1$	97-117	13.6	4.57	6.21	1.14	0.16	0.20	12.28	1.32	88.8	0.98	0.02
	51-3/9	$4Btgb_2$	117-147	9.5	3.23	4.65	0.91	0.07	0.35	9.21	0.29	93.3	0.96	0.04

CEC: capacity exchange cation; Ca^{2+}: calcium; Mg^{2+}: magnesium; Na^{+}: sodium; K^{+}: potassium; Al^{3+}: Aluminum; ECEC: effective cation exchange capacity; V: base saturation; ∑Cat.: sum of cations

Table 5.5D. Main physicochemical properties of the studied site. *Estancia* San Pedro: MOX-99/3

Side/ position	Reference	Depth cm	Genetic horizon	pH (1/2.5)	E.C.1/5 (dSm^{-1}. 25ºC)	$CaCO_3$ eq. %	Text. Class USDA	Sand	Silt	Clay	O.C. %	N %	C/N	P Olsen mg/kg
								------------	%------------					
Side 1. back of the ridge	3/1	0-10	A_1	8.0	0.1	0	L	39.4	48.5	12.1	1.2	0.1	11.6	9
	3/2	10-27	A_2	9.4	0.3	5	SiL	23.0	54.4	22.6	0.3	-	-	126
	3/4	27-42	$Bwkn_1$	9.2	0.3	0	SiL	25.7	55.5	18.8	0.2	-	-	30
	3/3	30-60	2C	9.4	0.2	0	SiL	34.6	58.6	6.8	0.1	-	-	28
	3/5	71-89	3C	9.6	0.4	5	L	43.7	45.6	10.7	0.2	-	-	38
	3/6	80-150	$4Bwkn_2$	9.9	0.5	5	SiL	20.4	52.8	26.8	0.2	-	-	28
	3/7	150-180	5C	9.3	0.1	5	LS	79.6	13.5	6.9	0.1	-	-	23
	3/8	187-210	6Abkn	9.3	0.1	5	SiL	14.5	61.0	24.5	0.2	-	-	21
	3/9	210-220	6Bwknb	9.7	0.6	4	SiCL	19.0	50.8	30.2	0.1	-	-	8

pH: relation 1soil: 2.5distilled water; EC: electrical conductivity relation 1soil/5distilled water; $CaCO_3$ eq.: carbonates equivalent: Textural classes: L: Loam; SiL: silt loam; LS: loamy sand; SiCL: silty clay loam; Size limits of USDA, diameter in mm: sand (2.0-0.05); silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; N: total nitrogen by Kjeldahl method P: phosphorus by Olsen method

Table 5.5Dbis. Main physicochemical properties of the studied site. *Estancia* San Pedro: MOX-99/3

Side/ position	Reference	Genetic horizon	Depth (cm)	CEC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Al^{3+}	ECEC	V	ESP
				cmol+/kg							%	%
Side 1	MOX-99-3	A_1	0-10	9.30	4.29	3.40	1.40	0.21	-	-	100.0	15.0
Back of the		A_2	10-27	12.40	2.27	6.20	3.71	0.22	-	-	100.0	29.9
ridge		2C	30-60	-	11.56	4.73	6.15	0.11	0.55	-	-	-
		6Bwknb	210-220	-	8.56	4.91	7.28	0.11	0.20	-	-	-

CEC: capacity exchange cation; Ca^{2+}: calcium; Mg^{2+}: magnesium; Na^{+}: sodium; K^{+}: potassium; Al^{3+}: Aluminum; ECEC: effectively capacity exchange cation; V: base saturation; $\sum$Cat.: sumation cations. ESP: exchange sodium percentage.

Table 5.5E. Main physicochemical properties of the raised field studied. *Estancia* Moxitania: MOX-99/8

Side/ position	Reference	Genetic horizon	Depth cm	pH (1/2.5)	E.C.1/5 (dSm^{-1}. 25ºC)	Text. Class USDA	Sand	Silt	Clay	O.C. %	N %	C/N	P Olsen mg/kg
							------------	%	------------				
Side 2 Ridge	8/4	A_1	0-11	4.9	0.06	SiL	16.9	59.9	23.2	1.8	0.2	9.0	5
	8/5	A_2	11-27	5.1	0.50	SiCL	14.2	58.6	27.2	0.9	0.1	8.7	2
	8/6	Btg_1	27-46	5.7	0.03	SiCL	13.4	58.6	28.0	0.5	-	-	2
	8/7	Btg_2	46-85	5.8	0.03	SiCL	11.1	58.6	30.3	0.5	-	-	2
	8/8	$2Cg_1$	85-102	6.4	0.04	SiL	10.2	76.6	13.2	0.2		-	4
	8/9	$3C_2$	102-137	6.3	0.03	Si	14.6	82.9	2.5	0.1	-	-	8
	8/10	$3C_3$	137-144	6.3	0.05	SiL	10.2	79.4	10.4	0.1	-	-	9
	8/11	4Btgb	144-197	6.6	0.04	SCL	73.1	5.7	21.2	0.1	-	-	9
Side 3 Channel	8/13	A_1	0-7	4.6	0.09	SCL	60.4	12.9	26.7	2.2	0.20	10.7	10
	8/14	A_2	7-20	5.1	0.05	SiL	21.0	55.6	23.4	1.0	0.10	9.9	3
	8/15	Btg_1	20-40	5.2	0.03	SiL	20.9	55.3	23.8	0.5	0.07	7.5	3
	8/16	Btg_2	40-63	5.3	0.04	SiCL	15.6	57.9	27.5	0.3	0.06	5.8	3

pH: relation 1soil: 2.5 distilled water; EC: electrical conductivity relation 1soil/5distilled water; $CaCO_3$ eq.: carbonates equivalent: Textural classes: Si: silty; SiL: silt loam; SiCL: silty clay loam; SCL: sandy clay loam; Size limits of USDA, diameter in mm: sand (2.0-0.05); silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; N: total nitrogen by Kjeldahl method; C/N; ratio total carbon/total nitrogen; P: phosphorus by Olsen method

Table 5.5Ebis. Cation exchange characteristics of the raised fields studied. *Estancia* Moxitania: MOX-99/8

Side/ position	Reference	Genetic horizon	Depth cm	CEC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Al^{3+}	CECE	CEC-ECEC	V %	∑Cat/CECE	Al^{3+}/CECE
					cmol+/kg									
Side 2	8/9	$3C_2$	102-137	1.95	0.13	0.75	0.14	0.06	-	-	-	55.4	-	-
Ridge	8/10	$3C_3$	137-144	5.18	1.20	2.10	0.20	0.05	-	-	-	68.5	-	-
	8/11	4Btgb	144-197	13.64	4.35	4.87	0.30	0.13	-	-	-	70.7	-	-
Side 3	8/13	A_1	0-7	11.15	1.47	1.44	0.14	0.10	-	-	-	28.4	-	-
Channel	8/14	A_2	7-20	9.40	2.00	1.17	0.06	0.11	2.15	5.49	3.91	35.5	0.61	0.39
	8/15	Btg	20-40	8.60	1.67	1.15	0.07	0.11	2.60	6.60	2.00	46.5	0.61	0.39

CEC: capacity exchange cation; Ca^{2+}: calcium; Mg^{2+}: magnesium; Na^{+}: sodium; K^{+}: potassium; Al^{3+}: Aluminum; ECEC: effective cation exchange capacity; V: base saturation; ∑Cat.: sum of cations

5.4.3. Micromorphological features

Figures 5.6 to 5.9 provide a detailed description of the studied *camellones* and the samples for micromorphological studies. The general micromorphological characteristics of the studied raised field soils are fine textures, with a practical absence of particles coarser than medium sand; an heterogeneous distribution of materials, with pockets of different colours and textures; striated b-fabrics due to argilloturbation related to the presence of smectite in these soils (Boixadera *et al.,* 2003), more or less expressed depending on the clay content; and very frequent lithological discontinuities along the profile. The main pedofeatures reflect the pedogenic processes in the area: clay mobilisation, waterlogging and biological activity. Although these characteristics are not substantially different from those of the natural soils from the Llanos (Boixadera *et al.,* 2003), their expression along the profiles (vertical variability) and also along from the microtopography from the *camellones* (horizontal variability) may give indications about the soil conditions and resulting from their construction.

The redoximorphic features are the most prominent characteristics of these anthropogenic soils: Fe-oxi-hydroxides form most of them, as matrix pedofeatures with different degrees of impregnation forming nodules (orthic or anorthic), and hypo- and quasicoatings; together with Fe-depletion microsites, either as pedofeatures (normally hypocoatings) or generalized in the groundmass.

Lindbo *et al.* (2010) propose a hierarchy of hydromorphic stages defined by seven sets of redoximorphic features, from low to high reduction, corresponding to increasing degrees of water saturation. From lower to higher waterlogging y it starts with intrapedal Mn-oxide (A) and Fe-oxide (B) nodules; Fe-oxide hypocoatings (C) and Fe-oxide quasicoatings together with Fe-depletion hypocoatings (D) on biopores while the groundmass remains oxidized; the same as D with clay-depletion hypocoatings (E); and Fe-depleted groundmass with Fe-oxide coatings and hypocoatings (F) and finally the same as F with Mn-oxide coatings on biopores. Roughly, these stages can be related with the stagnic (A to E) and gleyic (F, G) redoximorphic patterns of the World Reference Base described in the field (IUSS, 2014). We will use this classification to obtain an estimation of the length of the period of water reducing conditions in the soils.

Figure 5.6 and Table S5.4 displays the micromorphological characteristics of raised field MOX- 6 (*camellón*) with 2 profiles: one at the top of the ridge and one at the channel. Profile MOX 3 (undisturbed equivalent soil, data in Boixadera *et al.,* 2003) has been added only for comparison. Both soils are acidic: the lowest pHs at the raised field are found at MOX- 6 at the channel and at the upper part at MOX 3, where neutral pHs are found from 20 cm downwards (Boixadera *et al.,* 2003). Hydromorphy is more strongly expressed in MOX-6 channel; while MOX- 6 and MOX- 3 show similar hydromorphy degrees (Fig. 5.6). The sequences of hydromorphy class suggest stagnic conditions for MOX-3 and MOX-6 ridge (episaturation), and gleyic conditions for MOX-6 channel (endosaturation). Nevertheless, the abundance of anorthic nodules in MOX-6 ridge in opposition to the practical absence of them in MOX-3 could be an indication of the removal of material (landfill) when the *camellón* was built; therefore some of them could indeed correspond to inherited redoximorphic features from the original site. In this case, the drainage conditions of profile MOX- 6 ridge could be better than those of the undisturbed profile (MOX-3).

Almost all horizons (MOX-6) show signs of clay illuviation, either as anisotropic coatings or intercalations. These coatings are rarely pure: they have a dusty appearance due to mixture with silt, or are compound features with layers with fine sand .Nevertheless the coatings and inercalationtend to be more pure (more limpid in PPL) in the deep undisturbed Bt horizons similar to the yellowish coatings of undisturbed soils of the area (Boixadera *et al.,* 2003) (Table S5.4). These types of coatings have been attributed, in similar environments (Equatorian camellones) to old agricultural activities (Wilson *et al.,* 2002; Rodrigues *et al.,* 2015). In our case, they are present both in natural and anthropogenic soils, where, according to their morphology, they correspond to soil conditions with a high dispersion of material, that causes a low structural stability with pore collapse. Indeed, the microstructures of most of the horizons are apedal, without clear aggregate separation, with porosity due to faunal activity, that is the main agent responsible for the pore system. Also in the undisturbed underlying horizons it is quite common to observe remnents of sedimentary material with alternating horizontal layers of fine sand to coarse clay. These horizons show strong macrofauna activity. The analytical data of profile MOX- 6 show pH between 4.5-6.5 which is considered optimal for clay illuviation (SSS, 1999) (Table 5.4A). Ferrolysis processes seem unlikely, both from the morphological characteristics of the coatings (low anisotropy due to presence of coarser particles than clay, not to clay destruction), that differ from those reported in ferrolyzed soils (Ransom *et al.,* 1987) and also from the generalized presence of swelling clays in the groundmass. This is due to the non extreme acidity values (Van Ranst and De Coninck, 2002; Boixadera *et al.,* 2003; Van Ranst *et al.,* 2011). On the other hand, no buried A horizons are found in this soil: OC contents are higher at the topsoil and decrease regularly in depth.

The micromorphology of raised field MOX-51, is also shown in Table S5.5 for both microsites: upper sequence on top of the ridge (51-1) and lower sequence at the channel (51-3). They are also acidic soils (Table 5.4C), that tend to be more neutral in depth. The drainage conditions are also better at the top four horizons of the ridge (51-1), including a buried Abss horizon (Figures 5.6, 5.7,a,b) with a remarkable bioturbation (Figure 5.8); while at the bottom of this horizon and also at the drainage conditions are worse. Again, this situation would correspond to an endosaturation at the ridge, that could be partly due to the finer texture of the underlying horizons with strongly striated b-fabrics. The heterogeneity of the materials at the channel prevents a proper determination of the causes of water saturation. The clay mobility displays similar features as in raised field MOX-6: collapse of the pore system and frequent clay and silt (Figure 5.9c) and compound coatings and intercalations (Figure 5.8b), with practical absence of pure clay microlaminated coatings. Similarly as with MOX-6, pH falls in the range 4.5-6.5 for most the horizon.

Profile 99-8 is also an acidic profile, with OC decreasing with depth. Their micromorphological characteristics (Table S5.6) again show a worse drainage of channel sequence, apparently with episaturation (Figure 5.6), with strongly impregnated nodules, sometimes broken (Figure 5.7c); while the ridge has a better drainage at the top (endosaturation) (Figure 5.9a,b). Pedogenesis is expressed through an important clay mobilisation, with frequent clay intercalations and compound coatings due to collapse of the microstructure (Figure 5.8c). Fragments of sedimentary structures are found; turbulent flow takes place through large macropores due to biological activity and it carries suspended material to depth horizon where it sediments as thin layers in cavities. They resemble surface crusts when biological activity mixes to the soil and incorporate to the bulk soil (matrix).

Finally, profile 99-3 corresponds to a slightly sodic, alkaline soil. Besides the high pH (Table S5.6), P values are anomalously high in the whole profile. Calcium carbonate content reaches 5% in the bottom horizons and OM is decreasing in depth. The profile is highly disturbed by faunal activity and with numerous lithological discontinuities that indicate a high material heterogeneity. Nevertheless, fine material illuviation is generalized in the whole profile, with compound coatings and clay intercalations. Again, the drainage pattern indicates endosaturation, since the upper horizons seem better drained. The presence under the microscope of mm-size phytolith structures at the surface is also noticeable.

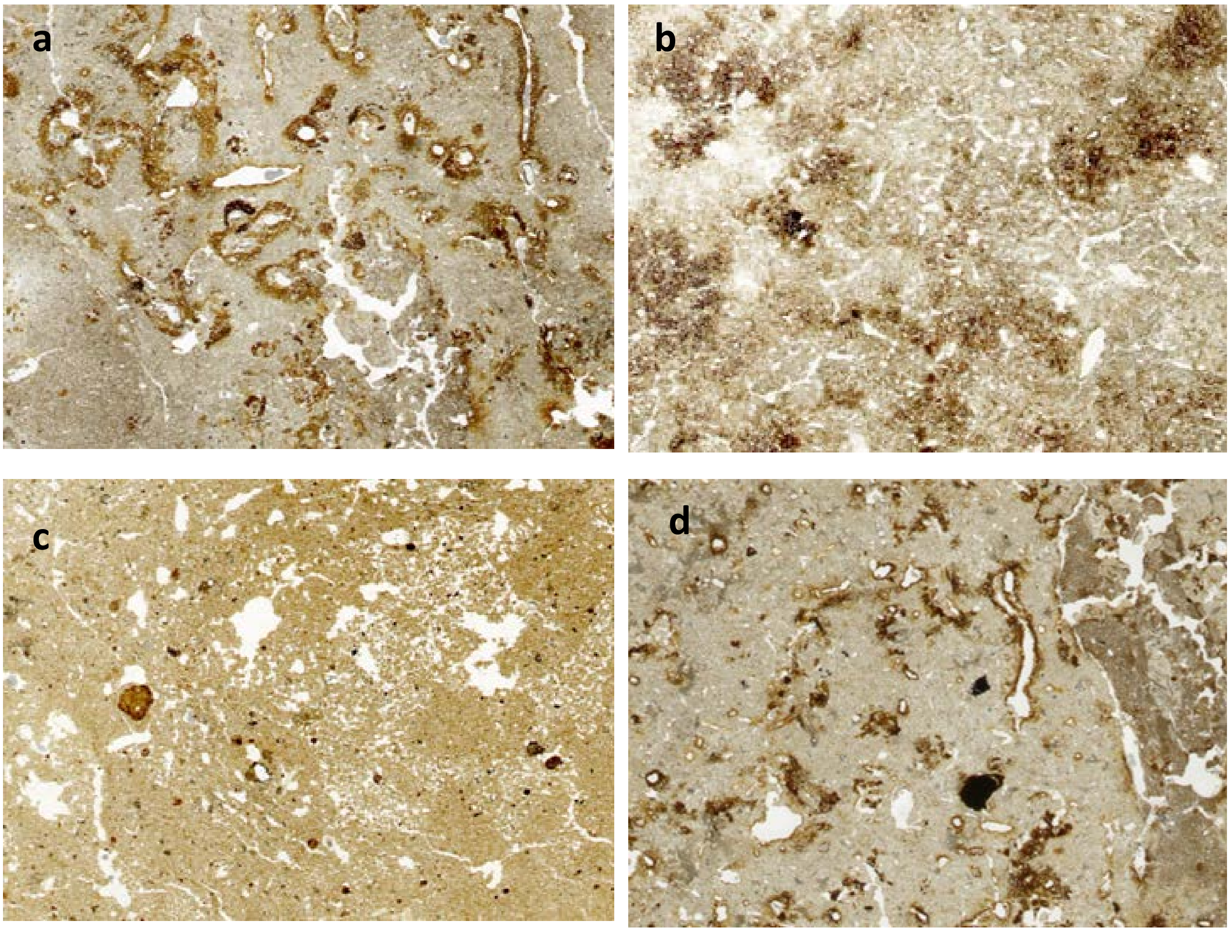

Figure 5.6. Scanned images of thin sections (size 3x4 cm) with redoximorphic feature classes according to Lindbo *et al.* (2010). (a) raised field MOX-6, channel, A_3 horizon (sample 6/8). Frequent Fe-depletion hycoatings and Fe-oxide quasicoatings; E-F class. (b) Raised field MOX-6, ridge Btg horizon. Impregnative orthic nodules of Fe oxides in the groundmass. B-C class. (c) Raised field MOX-51 (ridge), A_2 horizon. Anorthic rounded nodules of Fe-oxides and a high bioturbation. B class. (d) Raised field 99-8, channel, Btg_1 horizon. Hypo and quasicoatings of Fe-oxides, Fe-depleted groundmass. Note the faunal channel at the right of the image. F-G class

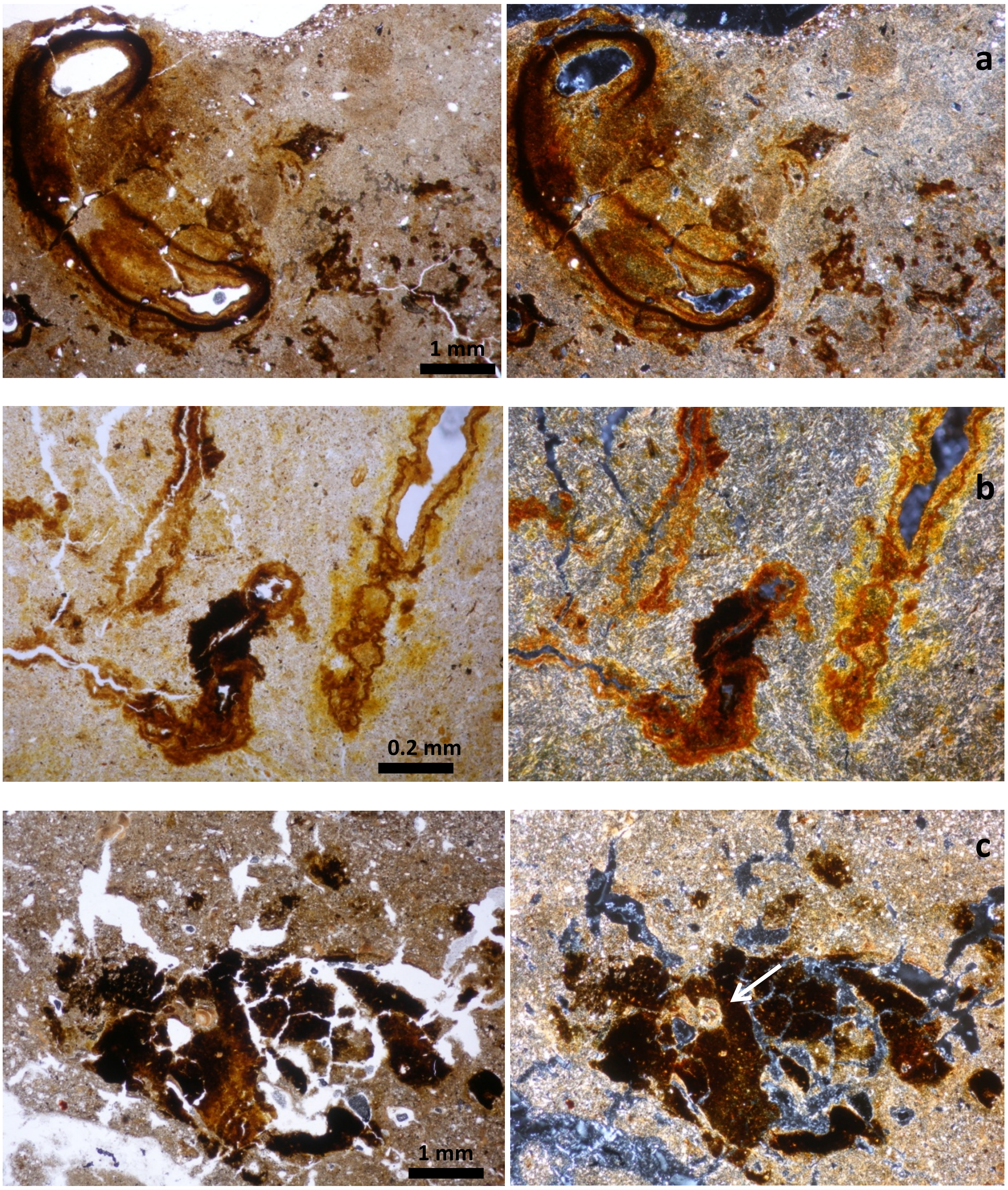

Figure 5.7. Redoximorphic features. (a) Sequences of quasi and hypocoatings of Fe-oxides around a channel. Raised field MOX-51, horizon 3Assb. (b) Channels and fissures with hypo- and quasicoatings of Fe-oxides, with different degrees of impregnation. Note the random-striated b-fabric in XPL. Raised field MOX-51 channel horizon 3Btgb$_1$. (c) Fragmented anorthic nodule of Fe-oxides, with a compound infilling (arrow) inside. Raised field MOX-99-8, channel horizon Btg$_2$. Images in PPL (left) and XPL (right)

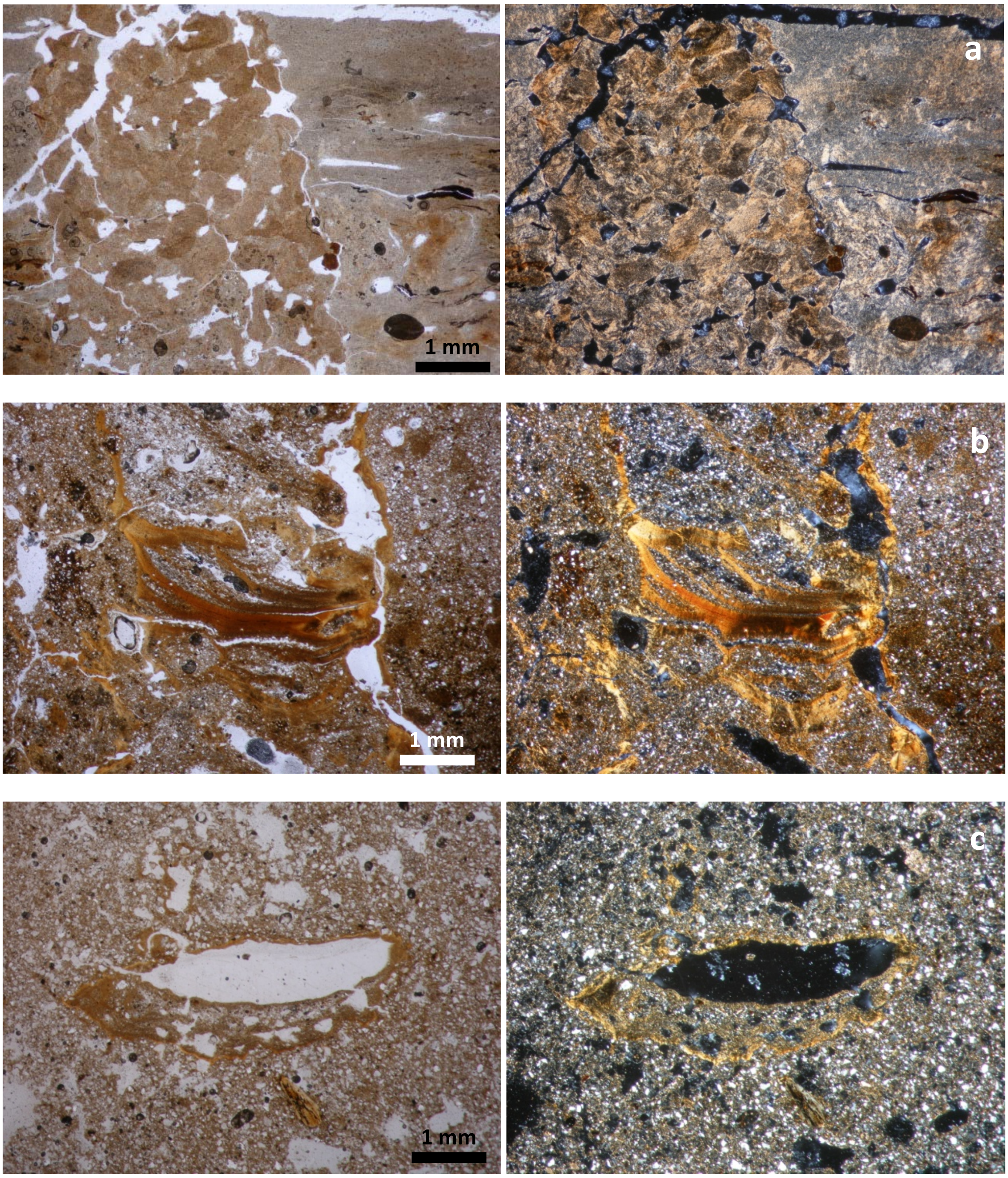

Figure 5.8. Fabric and textural features. (a) Excrement infilling of a faunal channel, showing a strong striation due to bioturbation. Raised field MOX-51, ridge horizon 3Abss. (b) Alternating clay and fine sand intercalations, probably due to structure collapse and/or turbulent flow. Raised MOX-51, channel horizon $2Bt_3$ (c) Compound coating of a cannel, alternating clay, silt and fine sand layers. Note the vesicular porosity of the coating but also in the groundmass, indicating trapped air due to aggregate collapse. Site MOX 99-3, Bwk_1. Images in PPL (left) and XPL (right)

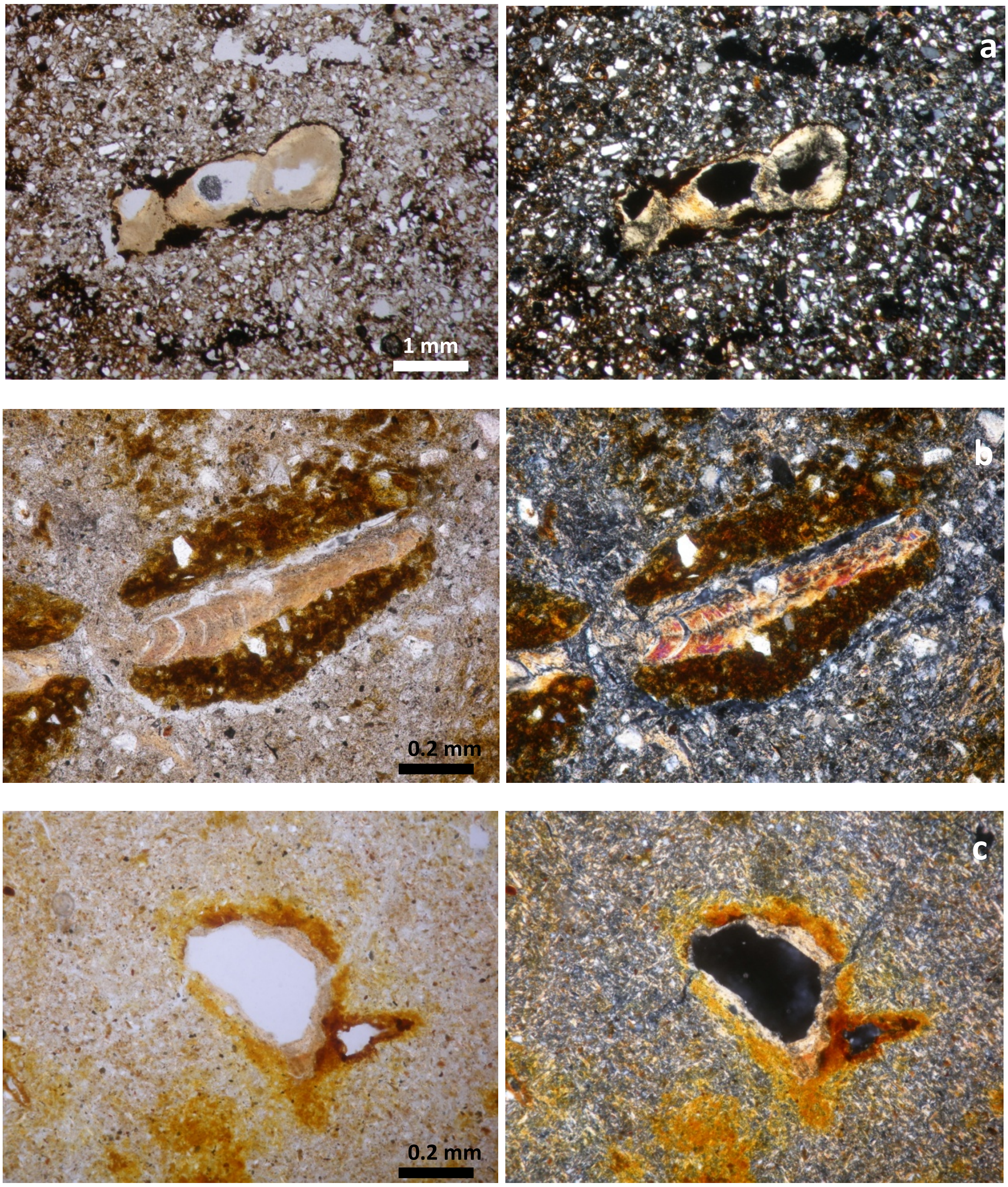

Figure 5.9. Compound features. (a) Clay coating overlying a Fe-oxide hypocoating. Note the low anisotropy of the coating, indicating a composition of a 1:1 clay. Raised field MOX-99-8, ridge horizon $2Cg_1$. (b) Infilling of a faunal channel surrounded by a moderately impregnated hypocoating of Fe-oxides. Raised field MOX-99-8, ridge horizon Btg. (c) Fine dusty clay and fine silt coating surrounded by a weakly (large pore) and moderately (smaller pore) impregnated hypocoating of Fe-oxides. Raised field MOX51, ridge horizon $3Btgb_1$. Images in PPL (left) and XPL (right)

5.4.4. Phytolith analysis

Table 5.2 and Figs 5.2 to 5.5 lists the provenance and Table description of the analyzed samples, and the main phytolith results, including the number of phytoliths per gram of soil, the total number of phytoliths morphologically identified and the percentage of weathered morphotypes, diatoms and sponge spicules. Phytolith concentration was very high in the three samples collected from the channels of the raised fields (MOX99-8/16, MOX-51-3/3 and MOX-6/15) ranging from 2.3 to 5 million phytoliths per gram of soil (g/soil) (Table 5.6). Samples from the ridge of the raised fields had a variable phytolith concentration: samples MOX-6/6 and MOX-51/4 contained 200,000 and 2,800,000 phytoliths g/soil, respectively. Phytoliths were absent in the sample collected from the site MOX-99-3-1/7 (Table 5.6); the high pH value (9.3) had probably caused phytolith dissolution (Table 5.3D). In sample MOX-6/6, only 50 phytoliths with consistent morphology were identified; additionaly, this sample presented a high % of weathered phytoliths (65%). The overall higher presence of big shape morphotypes (bulliforms and elongates) in the latter may be explained by some downward percolation of phytoliths through the soils. Thus results have to be taken with caution. Diatoms and sponge spicules were only identified in samples from raised field MOX- 51 although in low numbers (Table 5.6).

Table 5.7 lists the phytolith morphotypes recognized with a consistent morphology (weathered morphotypes were excluded here), their taxonomic association and their total and relative frequency in samples. A large variety of phytolith morphotypes (Figure 5.10a to 5.10p) were noted in all the soil samples. Poaceae phytoliths were the dominant vegetal component, whereas phytoliths from other families such as Cyperaceae, Arecaceae, Marantaceae and Eudicotyledonous plants (eudicots) were also identified. We observed 13 types of grass silicia short cells (GSSCs) corresponding to different grass subfamilies (Table 5.7). GSSC Short cell rondels and trapezoids were the most common and they are mostly found in Pooideae, Ehrhartoideae and Bambusoideae grass subfamilies in the Neotropics. GSSC bilobates (Fig. 5.10c-d), ascribed to the Panicoideae subfamily, were also recognized in high numbers. GSSC saddle collapsed (Fig. 5.10g-h) from the Bambusoid grass subfamily, was mainly identified in raised field MOX-51. Other GSSCs present although in lower numbers were crosses (Fig. 5.10g-h), saddles (Fig. 5.10i), trilobates, towers, oblongs, double-peaked glume cell (Fig. 5.10j) and rondel wavy top (Fig. 5.10k)(Table 5.7).

Table 5.6. Provenance and description of the analyzed samples, and the main phytolith results, including the number of phytoliths per gram of sediment, the total number of phytoliths morphologically identified and the percentage of weathered morphotypes, diatoms and sponge spicules

Site	Reference	Genetic horizon	Depth cm	Raised field	g/sed	Phytolits identified	WM %	Diatom %	Sponge Spicula %
***Estancia* La Vibora (MOX-6)**	MOX-6/15	Btg	43-68	ridge	5,000,000	227	15.69	-	-
	MOX-6/6	Btg	63-108	channel	200,000	118	65.63	-	-
***Estancia* Moxitania 1 (MOX-51)**	MOX 51-3/3	A_3	34-46	channel	2,300,000	260	13.66	1.46	-
	MOX 51/4	Bt	53-92	ridge	2,800,000	242	15.34	1.12	0.56
***Estancia* San Pedro (MOX-99-3)**	MOX99-3/1/7	C	150-180	ridge top	0	0	-	-	-
***Estancia* Moxitania 2 (MOX-99-8)**	MOX99-8/16	Btg	40-53	channel	4,000,000	280	17.36	-	-

WM: weathered morphotypes

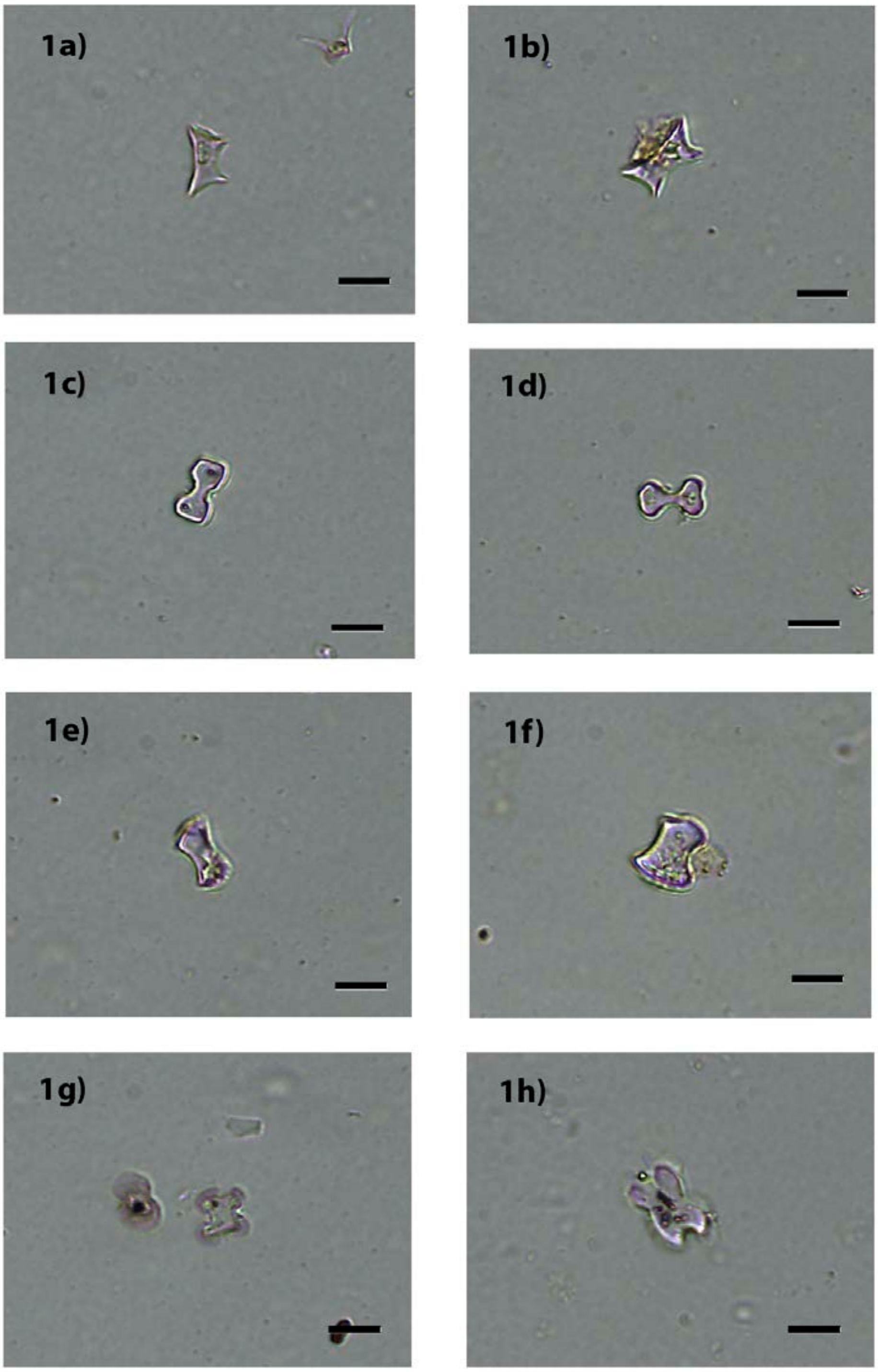

Figure 5.10. Microphotographs of phytoliths identified in samples. Pictures taken at 400 x. Scale bar 10µm a) GSSC rondel two picks (MOX99 8-16); b) GSSC rondel two peaks (MOX 51-4); c) GSSC bilobate ascribed to the Panicoideae subfamily (MOX99 8-16); d) GSSC bilobate ascribed to the Panicoideae subfamily (MOX 6-15); e) GSSC saddle collapsed from the Bambusoideae subfamily (MOX 51-4); f) GSSC saddle collapsed from the Bambusoideae subfamily (MOX 51 3-3); g) GSSC crosses (MOX99 8-16); h) GSSC crosses (MOX 51 3-3)

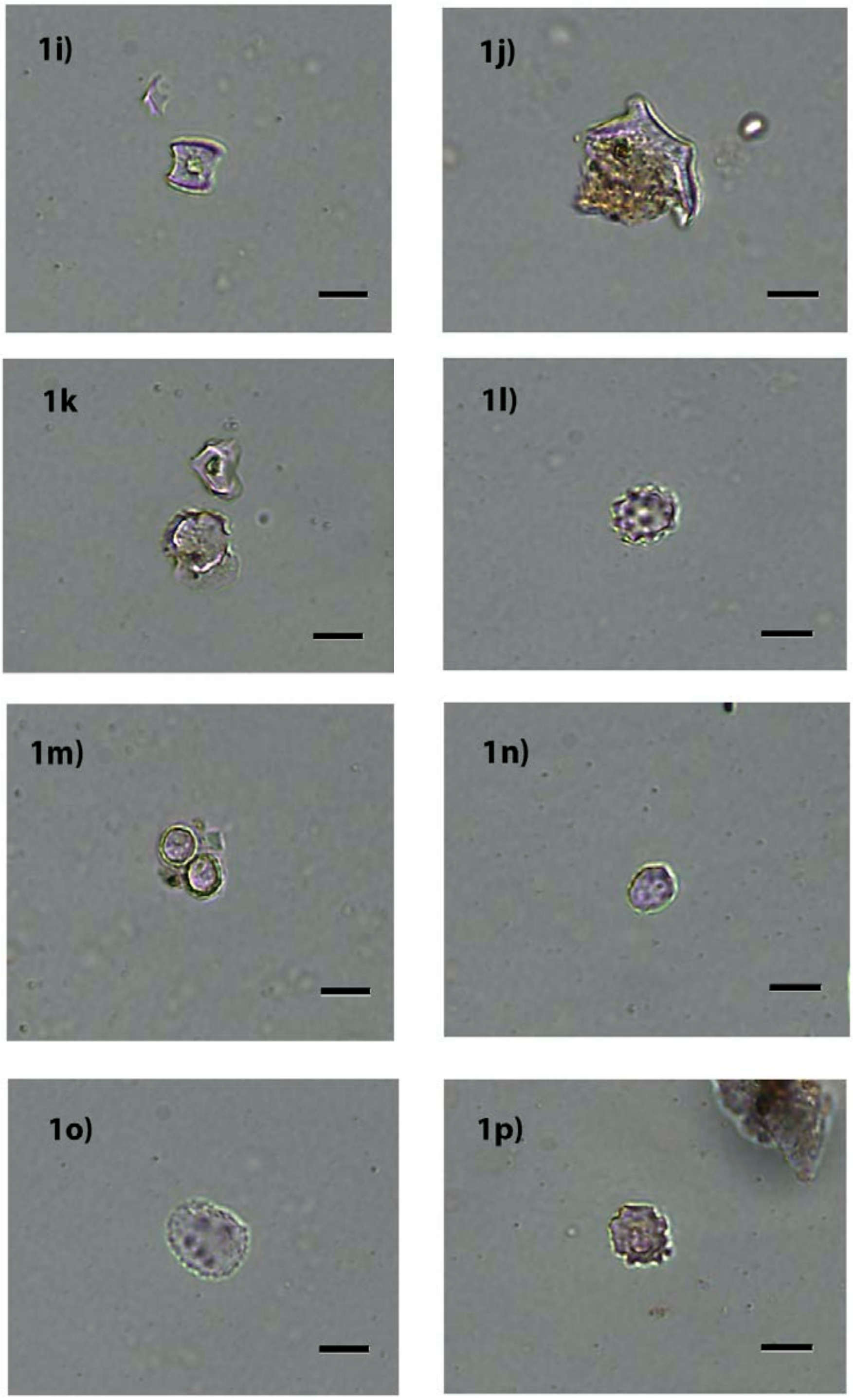

Figure 5.10 (cont.). Microphotographs of phytoliths identified in samples. Pictures taken at 400 x. Scale bar 10µm i) GSSC saddle from the Chloridoideae subfamily (MOX 51 3-3); j) GSSC double-peaked glume cell (MOX 51 3-3); k) GSSC rondel with wavy top ascribed to the Zea mays (MOX 51-4); l) Spheroid echinate from the Arecaceae family (MOX 51 3-3); m) Spheroids rugulate from the wood and bark of woody plants (MOX 6-15); n) Conical echinate from the Arecacea family (MOX 51-4); o) Conical echinate from the Arecacea family (MOX 51 3-3); p) Conical body probably from Ischnosiphon arouma (Marantaceae family) (MOX 51-4)

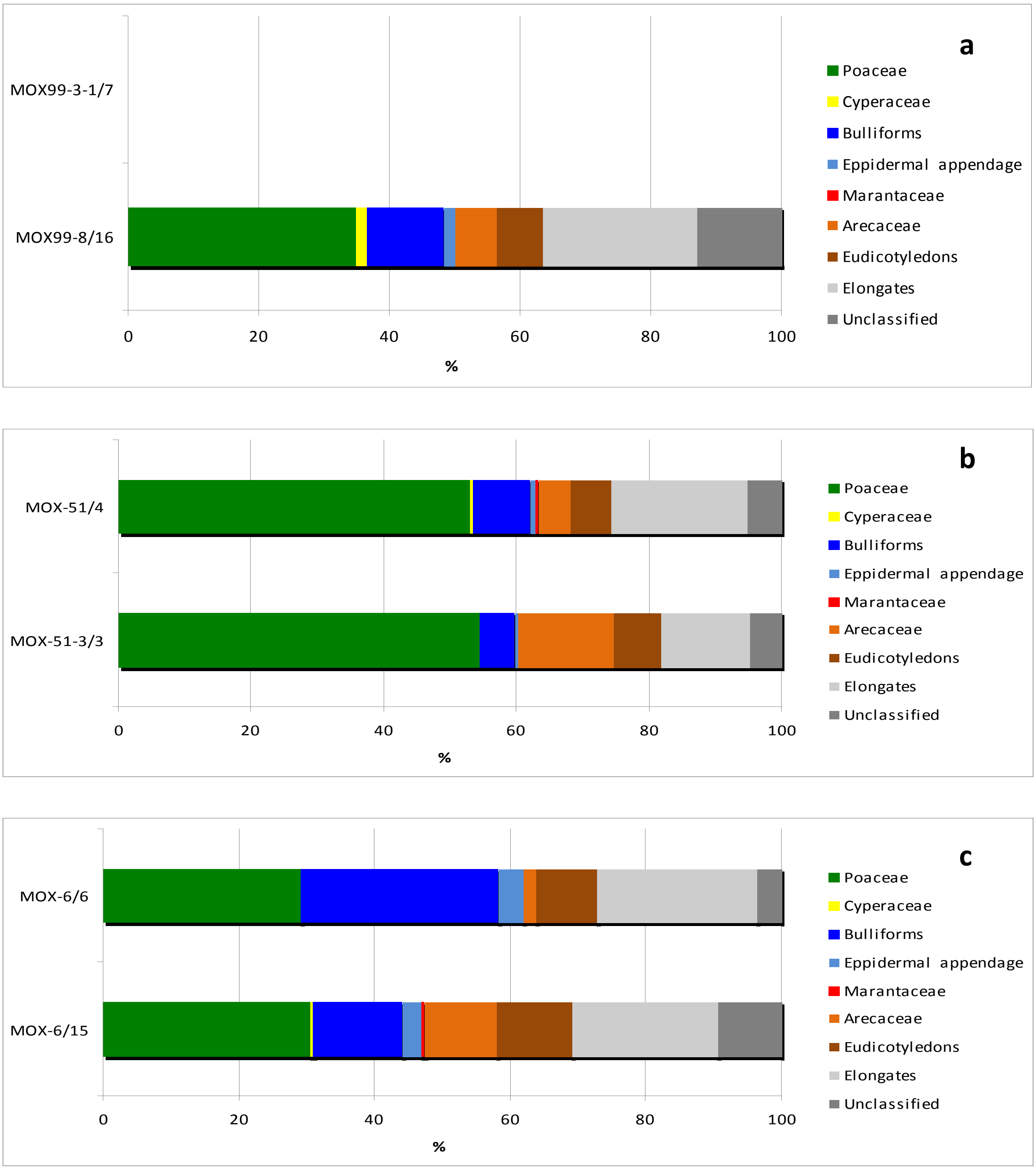

Figure 5.11. Histograms showing the relative frequencies of the phytolith morphological distribution among samples by plant types and plant parts. a) Raised field 99, b) Raised field 51 and c) Raised field 6

Raised field MOX-99/8

From this raised field, only one sample from the channel (MOX99-8/16) was studied, which showed high phytolith concentration (Table 5.61). This presented a high morphological variability, with grasses being the dominant plants (>44%) (Table 5.7 and Fig. 5.11a). The majority of the GSSCs identified were trapezoids (>60%) (Table 5.7). Bilobates constituted the second largest group (~20%) whereas other GSSCs from different grass subfamilies, such as saddle collapsed (Bambusoideae), bilobates (Panicoideae), saddles (Chloridoideae) and crosses were also identified (Table 5.7). Short cell rondels with wavy tops, probably from domesticated grasses, from the genus *Zea,* were also identified but in low numbers (Fig. 5.11b) (Piperno and Pearsall, 1993; Pearsall *et al.,* 2003).

Other families were represented by spheroid echinates phytoliths (Fig. 5.10l) from the Arecaceae family (7%). Cyperaceae cone-shape phytoliths had their highest concentration in this raised field (Table 5.7 and Fig. 5.11a). Eudicot phytoliths were also well represented, mostly by epidermal tissue (non-diagnostic), sclereid cells and tracheids. Spheroid psilates and rugulates (Fig. 5.10m) from the wood and bark of woody plants were identified in much lower numbers (Table 5.7).

Raised field MOX-51

The two samples collected from camellon MOX- 51 presented similar phytolith component and showed the highest Poaceae concentration (~60%) (Fig. 5.11b). GSSCs from this group were present in high morphological variety with trapezoids the most abundant (>50%) and mostly in sample MOX51-3/3, collected from the channel, where they reached the 74% (Table 5.7). The latter was the only sample where double-peaked glume cell phytoliths of the wild rices (Oryzoideae) was identified. Bambusoideae, Chloridoideae, Panicoideae and *Zea mays* (Fig. 5.10k) grass phytoliths were also observed although in very low numbers. GSSC crosses were identified in the samples from the ridge, although no taxonomic affinity could be assigned. Interestingly, GSSC towers, which are usually related to a forest grass understorey, were only identified in this raised field.

Characteristic Arecaceae phytoliths (spheroid echinate and conical echinate; Fig. 5.10n-o)), were identified in higher numbers in the sample from the channel (MOX-51-3/3). Cyperaceae phytoliths were only identified in the sample collected from the ridge (MOX-51-4). A single phytolith from the Marantaceae was recovered also from the later. This morphotype (Fig. 5.10p) described as a conical body by Watling and Iriarte (2013, see in Fig. 5.10o) was attributed by the authors to *Ischnosiphon arouma*. Eudicot plants were mainly represented by spheroid rugulate phytoliths from the wood and bark and tracheary elements and epidermal tissue (non-diagnostic) from eudicot leaves.

Raised Field MOX 6

The two samples collected from MOX-6 presented the lowest diversity of plant types of three raised fields studied. Morphological results from samples from the ridge (MOX6/6) have to be taken with caution because of the low number of phytoliths identified (mostly big-shape morphotypes such as bulliforms and elongates) and the high percentage of weathered morphotypes (Table 5.7). Poaceae, Arecaceae and eudicot plants were the only taxonomic groups identified through the phytolith record in both samples (Fig. 5.11c) although grasses were identified in higher numbers in the sample from the ridge (60%). In relation to GSSCs, oblongs, trapezoids and bilobates were the only morphotypes recorded in sample MOX6/6, collected from the ridge of the raised field. Conversely, sample MOX6/15 presented a higher variety of GSSCs. In addition to bilobates and trapezoids, crosses and rondels with wavy tops from *Zea mays* were also well represented (Table 5.7). Phytoliths characteristic of the Bambusoideae subfamily were not recorded in these samples.

Arecaceae phytoliths were present in both samples, being observed in higher numbers in the sample from the channel (MOX 6/15) as occurred in raised field 51. Eudicot phytoliths were identified in both samples, mainly represented by spheroid rugulates from the wood and bark and epidermal tissue from the leaves.

5.4.5. Humus datting

The measured humus ages are for the Assb horizon (raised field MOX-51), buried more 140 cm deep is (cal age) between (*68% range): 7625 – 7712 BP, with a calendaric age (ca): 5719 ± 43 BC.*

Table 5.7. Phytolith morphotypes recognized with a consistent morphology, their taxonomic association and their total and relative frequency in samples

Phytolith morphotypes	Taxonomic association	MOX99-8/16		MOX-51/4		MOX-51-3/3		MOX-6/6		MOX-6/15	
		n	%	n	%	n	%	n	%	n	%
ShC Collapsed saddle	Bambusoideae	3	1.26	10	4.69	17	7.42	0	0.00	1	0.41
ShC double-peaked glume cell	Oryzoideae	0	0.00	0	0.00	1	0.44	0	0.00	0	0.00
ShC rondel wavy top	Zea mays	1	0.42	2	0.94	2	0.87	0	0.00	3	1.22
ShC saddle	Chloridoideae	1	0.42	3	1.41	5	2.18	0	0.00	5	2.04
ShC bilobate	Panicoideae	19	7.98	12	5.63	5	2.18	7	12.73	33	13.47
ShC bilobate thick trapezoid	Poaceae	1	0.42	13	6.10	1	0.44	0	0.00	0	0.00
ShC cross shape (all variants)	Poaceae	5	2.10	6	2.82	1	0.44	0	0.00	5	2.04
ShC trilobate	Poaceae	0	0.00	0	0.00	1	0.44	0	0.00	1	0.41
ShC rondel/trapezoid (all variants)	Poaceae	43	18.07	64	30.05	71	31.00	3	5.45	20	8.16
ShC tower	Poaceae	0	0.00	1	0.47	3	1.31	1	1.82		0.00
Oblong trapeziform ShC	Poaceae	5	2.10	0	0.00	15	6.55	2	3.64	0	0.00
Long cell with decorated surfaces	Poaceae	5	2.10	2	0.94	3	1.31	3	5.45	7	2.86
Epidermal appendage (hairs and trichomes)	Poaceae and Cyperaceae	4	1.68	2	0.94	1	0.44	2	3.64	7	2.86
Bulliform fan-shape	Poaceae and Cyperaceae	28	11.76	17	7.98	11	4.80	16	29.09	32	13.06
Bulliform granulate	Poaceae and Cyperaceae	0	0.00	1	0.47	1	0.44	0	0.00	0	0.00

n: number of individuals for each specie; %: number of individuals each specie expressed in percentage

Table 5.7. Phytolith morphotypes recognized with a consistent morphology, their taxonomic association and their total and relative (cont.)

Phytolith morphotypes	Taxonomic association	MOX99-8/16		MOX-51/4		MOX-51-3/3		MOX-6/6		MOX-6/15	
		n	%	n	%	n	%	n	%	n	%
Cone-shape (hat shape)	Cyperaceae	4	1.68	1	0.47	0	0.00	0	0.00	1	0.41
Spheroid echinate	Arecaceae	15	6.30	8	3.76	17	7.42	1	1.82	26	10.61
Conical echinate (hat shape)	Arecaceae	0	0.00	2	0.94	16	6.99	0	0.00	0	0.00
Marantaceae seed	Marantaceae	0	0.00	0	0.00	0	0.00	0	0.00	1	0.41
Conical shape - Marantaceae	Marantaceae – Ichnosiphon arouma	0	0.00	1	0.47	0	0.00	0	0.00	0	0.00
Spheroid psilate	Woody plants	1	0.42	0	0.00	0	0.00	0	0.00	1	0.41
Spheroid rugulate	Woody plants	2	0.84	3	1.41	1	0.44	3	5.45	5	2.04
Large spheroid rugulate	Woody plants	0	0.00	2	0.94	0	0.00	0	0.00	0	0.00
Sclereids	Woody plants	2	0.84	0	0.00	0	0.00	0	0.00	0	0.00
Tracheids	Woody plants	2	0.84	2	0.94	1	0.44	0	0.00	0	0.00
Blocky Polyhedral	Woody plants	2	0.84	1	0.47	2	0.87	1	1.82	4	1.63
Brachiforms	Leaves woody plants	0	0.00	0	0.00	0	0.00	0	0.00	1	0.41
Parenchyma and related tissues	Leaves woody plants	7	2.94	5	2.35	12	5.24	1	1.82	7	2.86
Hair cell eudicots	Leaves woody plants	1	0.42	0	0.00	0	0.00	0	0.00	9	3.67
Elongates	Non-diagnostic	56	23.53	44	20.66	31	13.54	13	23.64	53	21.63
Unclassified		31	13.03	11	5.16	11	4.80	2	3.64	23	9.39

n: number of individuals for each specie; %: number of individuals each specie expressed in percentage

5.5. Discussion

5.5.1. Main features of the soils of San Ignacio de Moxos Area

The San Ignacio sector is located between the Mamoré and Beni rivers, two of the main tributaries of river Madeira, a white waters river. Although between Trinidad and San Borja some areas which are not often flooded - if ever - exist, most of the area traps part of the sediments of the waters of these rivers coming from the Andes, that are carrying significant amounts of materials and cations (Guyot, 1993). In other areas the flooding is due to poor drainage (Haase, 1992). To understand the characteristics of these soils it should be kept in mind that the Madeira river is the only one flooding the Amazonia lowlands that transports minerals in the suspended load (mica, illite, chlorite and feldspars) which have undergone minor changes through tropical weathering (Irion, 1984).

Soils between Mamoré river and San Borja in the San Ignacio sector shows good relationship with landscape features, specially vegetation. Parent material, particle size, are not easly related to present landscape and it should be taken into account the part river dynamics as well as the role of the minor rivers, other than Mamoré and Beni, which have constructed a minor system levees basin and backswamps with a larger system of rectangular lakes.

Hydromorphism is the dominant driving force in the pedogenesis of these soils. Yearly temporal flooding leaves imprint in the soil in the form of clear redoximorphic features.

Upon foofing important processes (Morh *et al.,* 1972) taking place in soil are: stabilization of the pH between 6.5 and 7.0, considerable increase of Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, $H_2PO_3^{-}$, HCO_3^{-} in the intersicial water. The increase in the concentration of cations Ca^{2+}, K^{+}, Na^{+},etc…, may be attributed to ion-exchange processes involving the adsorption of Fe^{2+} and Mn^{2+} (Morh *et al.,* 1972).

The large amount of cations to the solution from the exchange complexes leads to potential their leaching (fenolysis; vanRanst *et al.,* 2011; Duchafour 1982). The available data shows downward increase of cations saturation (V; Table 5.5Abis to 5.5Dbis) and little effect of plant recycling (upward trend). It could also be responsible of *salitrales* (Hanagath, 1993) and anomalous exchange composition (Mg^{2+} dominant) is several profiles.

In acids soils flooding results in the precipitation exchangeable aluminium (Sanchez *et al.,* 1980).

Large differences in drainage conditions may be foud in the studied soils and these different drainagle conditions are clearly related to landscape position.

Buried paleosols are found very often. Rodrigues *et al.* (2015) dated one in the banks of Mamoré at 5,000 years BP. In the raised fields we study there are several of them; onoe has been dated at about 5,500 years BP, well in agreement with results reported by Rodrigues *et al.* (2015). In other profile from the basin pasture near San Ignacio many other Ab horizons have been found. Althrough the profile described by Rodrigues *et al.* (2015) is clearly realated to the dynamics of the Mamoré river the other buried horizons are related to the interfluvial dynamics drived by the large fluctuaction in the yearly floodings (from 8,000 km^2 to 100,000 km^2; Hamilton *et al.,* 2000).

Other dominant soil forming process is clay (and silt) illiviation. Boixadera *et al.* (2003) reported clay illuviation as a dominant process in many natural soils of San Ignacio sector, being its micromorphological expression masked are defined (SSS, 1999), among other characteristics, by the presence of the more than 1% oriented clay and are named Bt under the Soil Taxonomy standards. In the lower (undisturbed) part of the raised fields several argilic horizon are found and our humus dating points out a time span for its formation of about 5,500 BC.

Temporal flooding and drying and pH range of these soils (from 4.3-6.5 in most cases) seems to produce optimal conditions for clay illuviation as been pointed out by several authors (Duchafour, 1982; Fanning and Fanning*,* 1989; SSS, 1999). As it follows from Bockheim and Hartemink (2013) review available information about the formation of such studied and widespread argilic horizon is searce but but the data available in the Llanos de Moxos fits in their data and demonstrate the importance of the local conditions upon the speed of the soil formation process.

Aluminium saturation (Table S5.4) is low in most of the profiles, in agreement with ideas of Sanchez *et al.* (1980) that the redox processes produces exchangeable aluminium precipitation.

Some soils with sodium (*salitrales*) are found, but they do not seems to present a significant extent.

Flooding of soils increases soluble and extractable soil P (Patrick *et al.,* 1985). This increase in available involves a reduction of ferric phosphate to ferrous forms , the hydrolysis of Fe and Al phosphate as pH increases and the dissolution of Ca phosphates because of higher CO_2 pressure in the soil solution; also in acid soils containing free Fe oxides, part of the occluded phosphate forms are released.

Alternanting anaerobic and aerobic conditions, as the case in most Moxos soils, causes marked fluctuations in soluble and extractable P. Usually P solubility, increased during flooding decreases upon drying (Patrick *et al.,* 1985). Because of the high chemical reactivity soluble phosphates are rapidly adsorbed and their availability decrease sharply.

The Olsen method only extracts part of the total soil P. It has been shown that in acid to neutral soils Al-P and any Ca-P the primary source of plant availability P (Kamprath and Watson, 1980) and this method gives a good measure of these forms. It seems do not react Fe-P (Thomas and Peaslee*,* 1973) and so it will underestimate P available, although this information is contradictory. Chang (1976) concluded that Olsen method is the most universally applicable to all type of soils and that aerobic and anaerobic P were highly correlated regarless of pH. From the available (Table S5.1) data we may conclude these soils falls in the normal range and present a certain variability among.

5.5.2. Distribution of raised fields

The marks of ancient land use, found in the area, in the form of earth works have been almost unnoticed until now due to the close vegetation. They are clearly man made and there are no grounds to support a natural origin like the case described by Jacob (1995) for the Maya Lowlands. Earlier investigations (Erickson, 1995; Walker, 1997; Lombardo, 2010) have suggested some general distribution, in relation with the geomorphology (Walker, 2008) but the available information is too fragmentary to establish a clear soil-geomorphological relationship among the sites where they are, and the present soil-drainage conditions. Perhaps these relationships – if they exist – are obscured by the changing pattern of a flood-plain and the growth of vegetation. It is assumed that raised fields were built under herbaceous vegetation (Erickson, 1995), although not evidences have been found until now for that statement.

Our research relates raised fields with earthworks (mounds, ditches, causeways), as other authors did (Erickson, 1995) but it also shows that there are no clear relationship between the sites where raised fields were built and geomorphology. Our work clearly indicates that raised fields were built to improve soil physical conditions, probably drainage, with nutrient aspects only minor. From this point of view the very different drainage conditions (Table 5.5A to 5.5D; Table S5.4 to S5.6) of the raised fields that we studied may be explained only from two aspects: the large inter annual (long-term) variability of flooding (currently from 8,000 to 100,000 Km depending on year, Guyot, 1993) and the wish and the need for local people to have suitable land for cultivation under different water regimes.

5.5.3. Morphological, physico-chemical properties of raised fields and soil classification

A close examination of the data from the raised fields reveals a systematic variation from ridges to channels, for physical-chemical properties as well as for redoxomorphic and other morphological features (Tables 5.5A to 5.5D; Table 5.5Abis to 5.5Dbis; Table S5.4 to S5.6).

Ridges tend to have higher pH, and base saturation and lower exchange cations for similar depths from the present soil surface. These differences are larger than the ones commonly attributed to the random variation (up to 10%) among pedons, for these properties (Wilding *et al.,* 1983) and will be the result of the action of the soil forming processes from the time of the raised fields construction.

Matrix soil clour is consistently redder in ridges than channels, both in poorly drained soils (Table 5.4A, D) and moderately well drained (Table 5.4B); mottling showns clearly, as it is expected, a similar pattern. Redoxomorphic pattern (stagnic or gleyic) is different in ridges and channels evaluated through micromorphological analysis using Lindbo *et al.* (2010) ideas; thus ridges have a glyic pattern and channel a stagnic one, showing the flux of soil water in the ridge-channel system.

Lack of abrupt horizon boundaries in the profiles may be attributed to the high biological activity, makig the possible discontinuities created by the building of the raised fields. The organic carbon distribution (SSS; 1999) retains its fluventic characteristics (> 0.2% organic carbon at 125 cm) with regular decrease at depth except when Ab horizon is present (MOX-51; MOX-99/8) or textural discontinuity (MOX-99/3).

Base saturation shows a downward trend, both in ridges and channels as a result of an overall leaching of cation, enhanced by the reduction processes.

Phosphorus Olsen shows and upward trend as a result of plant cycling, but no other patern seems identificable except in MOX-99/3 where it attest and antrophogenic unknown activity. Natural patterns of P content are identificable among the pampa (low P content) and forest (higher P content) (Table 5.3). Anthropic activities related to fertilization can not be identified through the P content of the studied raised fields.

The humus dating from the Assb horizon of MOX-51 tells us that the argilic horizon where the raised field was built has an age than more 5.500 BC. This is an unique mesurement but its much older than the data given by several authors (Erickson, 1995; Rodrigues *et al.,* 2015) for the raised fields.

Modern soil taxonomies (Soil Taxonomy, World Reference Base) are based on morphometric characters, especially the ones observable or measurable in the field, although in practice they often rely on soil analysis. According to our data, raised field soils have a set of properties which may be used for classification, and in our opinion they cannot be developed in a few tens of years. Among them we should mention: different pH, Al-saturation and drainage status between the ridge and the channel; similar color and P content than the surrounding, not strongly modified soils; no (or very few) artifacts and charcoal.

Landform features or historical data, termed by Evans *et al.* (2000) relational data, could be used to classify these soils, but this means a strong departure from the present classification systems although World Reference Base (IUSS, 2014) recognize the use of historical recods to identify an irragnic horizon. In summary, they do not fit into the scheme proposed by Kämpf *et al.* (2003) and to classify them in terms of top soil characteristics or as a soil phase is not fully satisfactory.

Kämpf *et al.* (2003), speaking about the so called Amazonian Dark Earths and the soil-forming processes acting on them suggests that the *camellones* of Llanos de Moxos could be included under the anthropogeomorphic processes. Perhaps they could belong to *terras mulatas* (Wood and McCaan, 1999; Kämpf *et al.* 2003), with colours 10YR4/2 or darker, P and Ca levels not higher than non-anthropogenic soils, rare cultural artifacts and higher content of charcoal (result of long term management, including burning).

5.5.4. Raised field soil conditions and crop growth

All our raised fields are moderately acidic (4.5-5.5) in the topsoil A horizons and slightly acidic (5.5-6.5) in the subsoil (Summer and Noble, 2003), apart from the MOX-93 which is not. The characteristics of the lastest soil relate to *salitrales* mentioned in other studies (Hasse, 1992; Boixadera *et al.,* 2003) but in fact corresponds to the western part of a sodic soil area, more prominent to the west and south (Pantanal, *el Chaco*). Although MOX-93 is different from the other studied raised fields, it demonstrates, in our opinion, that chemical soil conditions were not very important in the selection of areas for raised fields building. The present sodic (alkaline) conditions makes difficult to explain its intensive use (high P content), also related to maize cultivation (Tables 5.7 phytholiths).

Under acid conditions aluminum toxicity is the main limiting factor, although other elements may be harmful for crops (as Mn) and acidity goes together with low Ca and Mg and high Fe and Mn. Some authors consider maize (*Zea mays*) the main staple crop for the area at the time the raised fields were built and more sensitive than cassava (*Manihot*, sp.); therefore we will focus on it. It is believed that Al injuries to crops are due to Al in solution (Kamprath, 1984). Menzies (2003) stresses the difficulty of identifying Al-toxic soils indicating several criteria, among them pH and Al saturation. Some authors state that Al in solution is noticed when pH (H_2O) is below 5.5, but others state that the effect is only significant when pH is below 5.0. To assess these figures it should be considered that the critical pH at which Al becomes soluble in toxic concentration is also dependent on other soil factors: dominant clay, organic matter, other anions and cations and of course plant species (Foy, 1984).

Kamprath (1984) considers that when Al saturation is above 60% the soils have a detrimental content of Al for plants in the solution. Bruce (1986) quotes critical Al saturation for corn ranging from 5 to 70%, depending on soil type. With an Al saturation of less than 44%, Kamprath and Foy (1971) do not report damage to maize yield.

Taking all these facts into account we may conclude that in none of our raised fields Al toxicity was a very limiting factor for maize, and even less for cassava because it is a more resistant crop (Cock and Howell, 1978). In addition to that it should be kept in mind that there is a wide variability among species (Mengel *et al.,* 1982) and between the same species (Kamprath, 1984) to aluminum toxicity.

Phosphorus content, another limiting factor for high crop production, seems largely unchanged from that of the natural, surrounding soils and this means that no special cultural practices, such as fertilization, were adopted in the raised fields. In some cases the P contents are clearly higher (Table 5.5D) (MOX 99-3) and this supports the idea of a different land use, other than cultivation, as the artifacts indicate.

In order to fully interpret the P status of these soils we have to consider that when a dry soil is waterlogged it releases phosphates to soil solution from the ferric oxides. Something similar happens with Ca, Mg, K which are released from the exchange complex by manganous and ferrous oxides produced by waterlogging. It should be noted that the cations could be lost by leaching, but a closer look to the cation exchange complex of the raised fields (Table 5.5Abis to 5.5Dbis) do not support the idea that this could be a very important process.

Ridge soils have better chemical soil conditions for some parameters (pH, Al saturation, cations) than channel soils, but they are not significantly different than those in the surrounding soils.

Both macro and micromorphological studies demonstrate in all cases that drainage conditions are much better in the ridges than in the channels of the *camellones*. However there are very large differences between *camellones* with good drainage throughout the year (MOX 51). Although the lack of a closer monitoring prevents the assessment of the length of the saturation period, it can be drawn from the redoximorphic pattern. Crossley (2004) stresses the fact that more than the water coming from capillary rise (significant fluxes occur with heights of 30-45 cm, but also of 50-75 cm), protection against flooding is more important for the crops.

Camellones seem, therefore to invert the drainage conditions from episaturation to endosaturation, leaving the upper part of the profile with better drainage conditions

These facts reinforce the idea that *camellones* construction was intended to improve drainage conditions and/or water management, and not to improve soil chemical fertility.

5.5.5. Soil forming processes in the *camellones*

The chief soil forming processes affecting the raised field soils are clay illuviation, hydromorphism, leaching of cations and acidification, that are expressed in different degrees at a microscale (ridge/channel) in the raised fields.

All these soil forming processes are the same as in the natural surrounding soils and are reported elsewhere (Boixadera *et al.,* 2003). The differences in the *camellones* are the scale of expression (microtopography) and the intensity.

The *camellones* have changed the drainage of the ridges from episaturation to endosaturation in the channels. This is evident from the observed redoximorphic pattern, with the degree of episaturation (better drained) much lower than in the surrounding soils. Clay illuviation, and silt in many cases, is present already in the A_2 horizons under the form of impure, dusty coatings, somewhat different from the ones present in deeper B_t horizons. The low Al^{3+} saturation, more than ESP seems to be one of the reasons for these impure clay coatings.

5.5.6. Past land use of the *camellones*

Readily extractable P content has been used for the identification of anthropogenic soils (Lehman *et al.,* 2003) .In our case we used P Olsen, a standard method widely used in agriculture, instead of total P which is much more costly and difficult. Although there are shortcomings (better suited for calcareous soils, sensitive to redox situations) it is able to provide the broad, general picture we needed. The P data in depth exclude the idea of intentional or unintentional manuring of the camellones. *Camellon* MOX-99/3 is an exception, but P content may be directly related to the bones present in this case, which also denotes other landuses.

Whitney *et al.* (2013) found pollen from maize in their study with sediments from a rectangular lake near the study area. Juan-Tresserras *et al.* (2005) claim to have found significant quantities of maize (*Zea mays*) and cassava (*Manihot* sp.) pollen in MOX-6 and MOX-51. Since the soil pollen shows a mixed response of general and local origin we may accept that both crops were significant.

The phytolith study revealed a high variety of plant types, with Poaceae phytoliths dominant mostly in all the samples, mainly represented by grass silica short cells. Nevertheless, some differences were observed between the ridge (*a priori* cultivated soils) and the channels of the raised fields and between the three raised fields that preserved phytoliths.

When comparing the ridge and the channel samples, one remarkable fact is the higher presence of forest phytolith indicators (Arecaceae and eudicots) in the channel samples. During the raised field construction process, the soils removed from the channels were heaped into banks to conform the platforms for cultivation (the ridge). Thus, the presence of a phytolith arboreal component in the ridge of the raised fields might be explained by the contamination of phytoliths from previous vegetation when constructing the mounds. The same interpretation was also proposed in the *El Cerro* raised field site (Whitney *et al.,* 2014). In the same way, part of the phytolith assemblage observed in the channels might be representative of the past vegetation present previous to the construction of the raised fields.

Some differences among phytoliths were also observed in three raised fields, related to MOX- 99/8 and MOX-51 in comparison to MOX-6. The formers showed the dominance GSSCs of short cell rondel/trapezoid together with a higher presence of GSSCs saddle collapsed (Bambusoideae). These grass components (generally related to C_3 grasses) together with the arboreal component identified, suggest that the vegetation present in the different areas previous to the construction of these two raised fields was mostly a compound of mixed vegetation with the presence of an arboreal component of palms and other trees together with herbaceous plants, dominated by C_3 grasses. On the other hand, GSSCs were present in lower number in samples from the MOX-6 and were dominated by bilobates, implying a different grass species composition. This dominance of bilobates, probably from the Panicoideae subfamily, and also the high presence of arboreal components might be suggestive of a mosaic vegetation between wooded savannah and open savannah vegetation.

In relation to agricultural practices, phytoliths from domesticated plants (GSSC rondels with wavy tops from maize (*Zea mays*)) were identified although in very low numbers, both in the ridge and the channels. The reason for the presence of maize phytoliths in the channels may be due to its translocation from the top of the ridges. The low presence of cultivated plants was also observed in the phytolith study conducted in a raised-field site, *El Cerro*, located in the northwestern Llanos de Moxos that showed few diagnostic domesticated phytoliths (Whitney *et al.,* 2014). In any case the low presence of domesticated phytoliths is somehow expected because of the practically complete removal of the crops from the surface during harvesting, which might have left few phytoliths from these plants into the soil.

5.6. Conclusions

The San Ignacio de Moxos area has moderately acid soils and lacks strongly acidic subsoils. The flooding of the area with the white waters probably prevents strong acidification and flooding produces exchangeable Al precipitation. The main limiting factor for cultivation is poor both internal and external drainage. Textures range from sandy loam to heavy clay, but large areas have medium textures.

The pre-Columbian raised fields do not show any clear relationship with geomorphology, vegetation or soil types. This relationship is still obscure because available information is scarce and a significant part of the raised fields may be under forest. The raised fields are usually related to other earthworks (mounds, ditches, causeways…).

The raised fields studied have no artefacts, very little charcoal, no marks of tools and variable amounts of P, usually low. Redoximorphic features are present in most of the cases, but drainage is consistently better in the ridges, as should be expected.

Organic matter or nutrients are not higher than in the surrounding soils. They show slight to moderate acidity in the topsoil and very slight in the subsoil and therefore we may conclude that aluminum toxicity was not a major problem for agricultural use.

Phytolith analysis demonstrates that they were used for maize cultivation at some moment in the past.

Overall data do not seem to support the idea that fertility management was a main issue. Given the fact that all the raised fields have textures where the capillary fringe is important, we may think that water management played a role, perhaps extending the growing period in the dry season.

The illuviation of fine materials, clay and silt, is present in pores in all horizons of the ridged fields, showing the functionality of this process. We hypothesize that low Al-saturation may be the cause of the lack of flocculation of the fine material, in the absence of Na.

To reflect the anthropic character, the diagnostic factors that should be taken into account for soil classification are the surface morphology and the drainage pattern (ridges and beds), that strongly modify the length of waterlogging conditions at a microtopographic scale.

Supplementary material related to this article found, after references

References

Albert RM, Weiner S., 2001. Study of phytoliths in prehistoric ash layers using a quantitative approach. *In*: Meunier JD, Colin F (Eds.), Phytoliths, Applications in Earth Sciences and Human History, A.A. Balkema Publishers, Leiden, pp. 251–266.

Ayers, R. S., Westcot, D. W. 1985. Water quality for agriculture .Vol. 29, pp. 37-70. Rome: FAO.

Barba, J. 2003. Campos elevados- *In*: Moxos: una Limnocultura. Cultura y medio natural en el Amazonia Boliviana Romera I, Pasto J (Coord), pp. 89-94. CEAM. Barcelona, pp 212.

Belmonte JA, Barba J. 2011. Can nature align? The enigma of Moxos Lagoons, astronomy and landscape in south-western Amazonia. *Proceedings of the International Archonomical Union* ***7***(S278): 135-143. Oxford.

Benyarku CA, Stoops G. 2005. Guideliness for preparation of rock and soil thin sections and polishedsections. Quaderns DMACS, **33.** Universitat de Lleida.

Bockheim JG, Hartemink, AE. 2013. Distribution and classification of soils with clay-enriched horizons in the USA. *Geoderma* **209-210**: 153-160.

Boixadera J, Poch RM, García-González MT, Vizcayno C. 2003. Hydromorphic and clay-related processes in soils from Llanos de Moxos (northern Bolivia). *Catena* **54**: 403-424.

Brock F, Higham T, Ditchfield P, Ramsey CB. 2010. Current pretreatment methods for AMS radiocarbon dating at the Oxford Radiocarbon Accelerator Uit (ORAU). *Radiocarbon* **52**(1): 103-112.

Bruce RC. 1986. Diagnosis of aluminium toxicity and calcium deficiency in acid soils using soil and soil solution attributes. St Lucia, Australia. The University of Queenstand

CBDSA 1983. SINEDARES, Manual para la descripción codificada de suelos en el campo. Ministerio de Agricultura, Pesca y limentación de España, Madrid.

Chang SC, 1976. Phosphorus in submerged soils and phosphorus nutrition of rice. *In:* The fertility soils of paddy soils and fertilizer application for rice, pp. 93-116. Food and Fertilizer Techonology Center Taipei. Taiwan.

Cock J H, Howeler RH. 1978. *The ability of cassava to grow on poor soils. Crop tolerance to sub-optimal land conditions. American Society of Agronomy* **32***:* 145-154.

Denevan W. 2006. Una perspectiva histórica sobre el descubrimiento de campos elevados (camellones) prehispanicos en SurAmérica. *In:* Valdez F (Ed). Agricultura ancestral camellones y albarradas. Contexto social, usos y retos del pasado y del presente. Actos y memorias IFEA. Edicioens Abya-Yala, pp17-24 Quito. Ecuador.

Denevan WM, 1970. Aboriginal drained-field cultivation in Americas. *Science* **169**: 647-654

Denevan WM, William M, Turner II BL. 1974. Forms , functions and associations of raised fields in the old world tropics. *The Journal of Tropical Geography* **39**:24-33.

Dickau R, Whitney BS, Iriarte J, Mayle FE, Soto D, Metcalfe P, Street-Perrott, A, Loader NJ, Ficken KJ, Killeen TJ. 2013. Differentiation of Neotropical ecosystems by modern soil phytolith assemblages and its implications for palaeoenvironmental and archaeolog-ical reconstruction. *Review of Palynology and Palaeobotany* **193**: 15–37.

Duchafour R, 1982. Pedology. Pedogenesis and classification (translated by Paton TR). George Allen and Unwin, London.

Erickson CL, Walker J, Candler KL, Angle D, Michel M, Winkler W, Jacob J.1994. Arqueología de la agricultura de camellones e infraestructura hidraúlica en el departamento del Beni. La Paz.

Erickson CL. 1995. Archaeological methods for the study of ancient landscapes of the Llanos de Mojos in the Bolivian Amazon. *In:* Stahl PW (Ed.), Archaeology in the Lowland American Tropics, pp. 66-95. Cambridge: Cambridge University Press.

Erickson CL. 1996. Investigación arqueologíca del sistema agrícola de los camellones de la cuenca del Lago Titicaca del Perú, El Centro de Informacion para el Desarrollo (CID) y El Proyecto Interinstitucional de los Waru Waru (PIWA), La Paz.

Evans CV, Fanning DS, Short JR. 2000. Human influenced soils 33-67 *In* Brown RB, Anderson JL, Huddleston JD (Eds.). Managing soils in a growing urban area. AASA Monograph, 39, Madison. Wisconsin.

Fageria NK, Baligar, VC. 2003. Fertility management of tropical acid soil for sustainable crop production, pp. 359-386 In Handbook of Soil Acidity. Rengel Z. (Ed.). Marcel Dekker Inc., New York, pp. 495.

Fanning DS, Fanning MCB. 1989. Soil: morphology, genesis, and classification. John Wiley and Sons, New York, pp 395.

Foy CD. 1984. Physiological effects of hydrogen, aluminum, and manganese toxicities in acid soil. *In* Soil Acidity and Liming-Agronomy Monograph no. 12 (2nd Edition). ASA-CSSA-SSSA, 677 South Segoe Road, Madison, WI 53711, USA, pp 57-97.

Gonzales J, Aydin A 2008. The origino f oriented lakes in the Andean foreland, Parque Nacional Torres del Paine (Chilean) Patagonia. *Geomorphology* **97**: 502-515.

Google maps, 2015. https://www.google.es/maps (Bolivia, Moxos, Trinidad).

Guyot JL, 1993. Hydrogéochemie des fleuves de l'Amazonie Bolivienne. ORSTOM (Office de Recherche Scientifique des territories d'Outre Mer). Paris, pp.262.

Haase R. 1992. Physical ad chemical properties of savanna soils in Northern Bolivia. *Catena* **19**: 1119-134.

Hamilton SK, Sippel SJ, Melack JM. 2004. Seasonal inundation patterns in two large savanna floodplains of South America: the Llanos de Moxos (Bolivia) and the Llanos de Orinoco (Venezuela and Colombia). *Hydrology processes* **18**: 2103-2116.

Hanagarth W.1993. Acerca de la Geoecología de las Sabanas del Beni en el Noreste de Bolivia. La Paz: Instituto de Ecología.

Herrero J, Rodríguez R, Porta J. 1989. Colmatación de drenes en suelos afectados por salinidad, pp 134. Institución Fernando el Católico. Zaragoza.

Hinkel K, 2006. Comment on Formation of oriented thaw lakes by thaw slumping . *Journal of Geophysical Research,.* **111** (F1): 1-4.

Iriarte J. (2003) Assessing the feasibility ofidentifying maize through the analysis of cross-shape size and three-dimensional morphology of phytoliths in the grasslands of southeastern *South America. Journal ofArchaeological Science* **29**:1085-1904.

Irion G. 1984. Sedimentation and sediments of Amazonian rivers and evolution of the Amazonian landscape since Pliocene times, p 201-214. *In:* Sioli H (Ed). The Amazon Limnology and landscape ecology of a mighty tropical river and its basin. Klumer Academic Publishers Group. Dordrecht. Boston. Lancaster, pp. 763.

IUSS, 2014. World reference base data for soil resource 2014 . International soil classification system for naming soils and creating legends for soils maps 116 p 181. Disponible en: http://www.fao.org/3/a-i3794e.pdf.

Jacob JS 1995. Archaeological podology in the Maya Lowlands. *In:* Collins ME, Carter BJ, Gladfelter BG, Randal JS (Eds). Pedological perspectives in archaeological research, pp. 51-94. SSSA Special publication 44. Madison. Wisconsin.

Juan-Tresserras J, Villalba MJ, Playa RM, Comes M, Michel M. 2005. Arquelogia dels sistemes precolombians de producció (agricoles i aqüicoles dels LLanos de Moxos, Hoya Amazonica Boliviana). Tribuna de Arqueologia, pp. 225-242. Generalitat de Catalunya. Barcelona.

Kämpf N, Woods WI, Sombroek W, Kern DC, Cunha TJF. 2003. Classification of Amazonian Dark Earths and other ancient anthropic soils. *In:* Lehmann J, Kern DC, Glaser B, Woods WI (Eds.), Amazonian Dark Earths: Origin, Properties, Management, pp. 77-102. The Netherlands. Kluwer Academic Publishers.

Kamprath E J. 1984. Crop response to lime on soils in the tropics *In* Soil Acidity and Liming-Agronomy Monograph no. 12 (2nd Edition). ASA-CSSA-SSSA, 677 South Segoe Road, Madison, WI 53711, USA, pp 349-368.

Kamprath ES, Watson ME. 1980. Conventional soil and tissue test for assessing the phosphorus status of soils. *In:* The role of phosphorus in agriculture. Khassawneh et al. (eds), ASA, CSSA, SSSA. Madison. Wisconsin.

Kamprath ES, Foy CD. 1971. Lime fertilizer plant interactions in acid and soil , pp105-151. *In:* Olsen RW, Army TJ, Hanway JJ, Kilmer VJ. (Eds.). Fertilizer technology and use. SSSA. Madison. Wisconsin.

Katz O, Cabanes D, Weiner S, Maeir A, Boaretto E, Shahack-Gross R. 2010. Rapid phytolith extraction for analysis of phytolith concentrations and assemblages during an excavation: an application at Tell es-Safi/Gath. *Israel Journal of Archaeological Science* **37** (7): 1557-1563.

Lehman J, Kern DC, German LA, McCann J, Martins GC, Moreira A.2003.Soil fertility and production potential. *In:* Lehmann J, Kern D, Glaser B, Woods WI. (Eds.) Amazonian dark earths: origins, properties, and management. Dordrecht, pp105-124.

Lima H, Schaefer CER, Mellob JWV, Gilkes RJ, Ker JC. 2002. Pedogenesis and Pre-colombian *Geoderma* **110**:.1-17.

Lindbo DL, Stolt MH, Vepraskas MJ. 2010. Redoximorphic features. *In:* Stoops G, Marcelino V, Mees F. (Eds.). Interpretation of Micromorphological Features of Soils and Regoliths. Their relevance for pedogenic studies and classifications. Elsevier, pp 752.

Lombardo U, Canal-Beeby E, Fehr S, Veit H. 2011a. Raised in the Bolivian Amazonia: a prehistoric grren evolution or a flood risk mitigation strategy?. *Journal of Archaeological Science* **38**: 502-512.

Lombardo U, Canal-Beeby E, Veit H. 2011b. Eco-archaeological regions in the Bolivian Amazon. An overview of the pre-Columbian earthworks linking them to their environmental setting. *Geographica Helvetica* **66**: 173-182.

Lombardo U, Denier S, Veit H. 2015a. Soil properties and pre-Columbian settlement patters in Monumental mounds region of the Llanos de Moxos, Bolivian Amazon. *Soil* **1**: 65-81.

Lombardo U, May 2012 Veit JH, Veit H. 2012. Mid- to late-Holocene fluvial activity behind pre-Columbian social complexity in the southwestern Amazon basin. *The Holocene* **22**:1037-1045.

Lombardo U. 2010 Raised fields of northwestern Bolivia: A GIS based analysis.Zeitschrift für Archäologie Außereuropäischer Kulturen **3**: 127–149.

Lombardo U. 2015b. Alluvial plains dynamics in the southern Amazonian foreland basin. *Earth System Dynamics* **6**: 2063-2100.

Lombardo, U, Denier S, May JH, Rodrigues L, Veit H. 2013. Human-environment interactions in pre-Columbian Amazonia: The casse of the Llanos de Moxos, Bolivia. *Quaternary International* **312**: 109-119.

Madella M, Alexandre A, Ball TB, 2005. International Code for Phytolith Nomenclature 1.0. *Annals of Botany* **96**: 253-260.

MAPA, 1993. Métodos oficiales de análisis. Ministerio de Agricultura, Pesca y Alimetación de España. Madrid, Spain.

Mengel K, Kirkby EA. 1982. Elements with more toxic effects. *In*: Mengel K, Kirkby EA (Eds). Principles of plant nutrition, Third edition, pp559-571. International Potash Instute, Bern, Switzerland.

Menzies NW. 2003. Toxic elements in acid soils: chemistry and measurement, pp 267-296 *In:* Rengel Z (Ed.). Handbook of Soil Acidity. Marcel Dekker Inc., New York, pp. 495.

Morh ECS, van Baren FA, van Schuylenborgh J. 1972. Tropical soils comprensive study of their genesis. The Haque, pp. 481.

Mulholland SC, Rapp JrG. 1992. A morphological classification of grass silica-bodies. *In:* Rapp JrG, Mulholland SC (Eds.). Phytolith Systematics, Emerging Issues, Advances in Archaeological and Museum Science,Plenum Press, New York, pp. 65–89.

Nordenskiöld E, 1924. The ethnography of south-america as seen from Mojos in Bolivia . Comparative Ethnological Studies, 3 Göteborg, Sweden. Pehrssons Förlag.

Page AL, Miller RH, Keeney DR. (Eds). 1982. Methods of soil analysis: II. Chemical and microbiological properties, 2nd ed. ASA-SSSA, Madison, Wisconsin, USA.

Patrick WH, Mikkelsen DS, Wells BR. 1985. Plant nutrient behavior in flooded soil. *In:* Engelstad OP (Ed), Fertilizer Technology and Use, pp. 197-228. SSSA. Madison. Wisconsin.

Pearsall DM, Chandler-Ezell K, Chandler-Ezell A. 2003. Identifying maize in Neotropical sediments and soils using cob phytoliths*. Journal of Archaeological Science* **30**: 611-627.

Pipemo DR, Pearsall DM. 1998. The Silica Bodies of Tropical American Grasses: Morphology, Taxonomy, and Implications for Grass Systematics and Fossil Phjrtolith Identification. Smithsonian Contributions to Botany. Number 85. Smithsonian Institution Press, Washington DC.

Piperno DR, Pearsall DM. 1993. Phytoliths in the reproductive structures of maize and teosinte: implications for the study of maize evolution. Journal *of Archaeological Science* **20**: 337–362.

Piperno DR. 1984. A comparison and differentiation of phytoliths from maize and wild grasses: use of morphological criteria*. American Antiquity* **49**: 361–383.

Piperno DR. 1988. Phytolith Analysis: an Archaeological and Geological Perspective. Academic Press, San Diego, pp. 280.

Piperno DR. 2006. Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists. AltaMira Press, Lanham, MD, pp. 238.

Piperno DR. 2009. Identifyingcropplantswith phytoliths (and starchgrains) in Central and South America: A review and anupdate of theevidence. *Quaternary International* **193**: 146–159.

Plafker G. 1963 Observations on archeologycal remains in Northeastern Bolivia. *American Antiguity* **28**: 372-378.

Plotzki A, May JA, Preusser F, Veit. 2013. Geomorphological and sedimentary evidence for late Pleistocene to Holocene hydrological change the Río MAmoré, Bolivian Amazon. *Journal of South American Earth Sciences* **47**: 230-242.

Plotzki A, May JH, Veit H. 2011. Review of past and recent fluvial dynamics in the Beni lowlands, NE Bolivia. *Geographica Helvetica* **66:** 164–172.

Porta J, López-Acebedo M, Rodriguez R. 1986. Técnicas y experimentos de edafología, vol 1. Collegi Oficial d'enginyers agrònoms de Catalunya, Barcelona.

Prumers, H. 2009. "'Charlatanocracia' en Moxos?" In: Procesos y expresiones de poder, identidad y orden tempranos en Sudamerica. Vol.2 , (Eds.) Kaulicke P, Dillehay TD. *Boletin de Arqueologia PUCP* **11**: 103–116.

Rodrigues L, Lombardo U, Fehr S, Preusser F, Veit H. 2015. Pre-Columbian agriculture in the Bolivian lowlands: constructon history and management of raised fields in Bermeo. *Catena* **132**: 126-138.

Sanchez PA, Uehara G. 1980. Management considerations for acid soils with high phosphorus fixation capacity. *In:* Khasawneh FE, Sample EC, Kamprath, EJ (Eds). The role of phosphorus in agriculture. pp 471-514. ASA., CSSA, SSSA, Madison. Wisconsin.

Sombroek WG. 1966. Amazon Soils. A reconnaissance of the soils of the Brazilian Amazon region. Centre for Agricultural Publications and Documentation PUDOC, Wageningen, pp. 303.

SSS, 1999. Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. Soil Survey Staff. 2nd ed. USDA-NRCS. Washington.

SSS, 2014 Soil Survey Staff. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stoops G. 2003. Guidelines for analysis and description of soil and regolith thin sections. Soil Science Society of America Inc. Madison, Wisconsin.

Summer ME, Noble AD. 2003. Soil acidity: The world story, pp 1-28 *In:* Rengel Z (Ed.). Handbook of Soil Acidity. Marcel Dekker Inc., New York, pp. 495.

Thomas GW, Peaslee DE. 1973. Testing soil for phosphorus. *In:* Walsh L, Beaton J (Eds). Soil testing and plant analysis, pp. 115-132. SSSA. Madison. Wisconsin.

Twiss PC, Suess E, Smith RM. 1969. Morphological classification of grass phytoliths. *Soil Science society of America Proceedings* **33**(1): 109-114.

Van Ranst E, De Coninck E. 2002. Evaluation of ferrolysis in soil formation. *European Journal of Soil Science* **53**: 513-519.

Van Ranst E, Dumon M, Tolossa AR, Cornelis JT, Stoops G, Vandenberghe RE, Deckers J. 2011. Revisiting ferrolysis processes in the formation of Planosols for rationalizing the soils with stagnic properties in WRB. *Geoderma* **163**(3): 265-274.

Villaba MJ, Alesán A, Comas M, Juan Tresseras J, López Sáez JA, Malgosa A, Michel M, Playà R. 2004. Investigaciones arqueológicas en los Llanos de Moxos (Amazonía boliviana). Una aproximación al estudio de los sistemas de producción precolombinos. Bienes culturales. *Revista del Instituto de Patrimonio Español* **3**:201-215.

Walker JH. 1997. Arquelogía de un paisaje agrícola en la provincia de Yucama. Departamento del Beni, Bolovia. Informe preliminar de las investigaciones del Beni en las cuencas agro-arqueológiccas del Beni en la cuencas de los ríos Iruyañez y Omi en 1996-1997. 4 diciembre 1997, pp. 136.

Walker JH. 2003. Agricultural Change in the Bolivian Amazon. Latin American Archaeology Reports, Pittsburgh: University of Pittsburgh.

Walker JH. 2008. Chapter 46. The Llanos de Mojos, pp 927-939. In (Eds) Silverman H, Isbell W. Handbook of South American Archeology. Springer. New York.

Wattling S, Iriarte J. 2013. Phytoliths from the coastal savannas of French Guiana. *Quaternary International* **287**:162-180.

Whitney BS, Dickau R, Mayle FE, Soto JD, Iriarte J. 2013. Pre-Columbian landscape impact and agriculture in the Monumental Mound region of the Llanos de Moxos, lowland Bolivia. *Quaternary Research* **80**: 207-217.

Whitney DS, Dickau R, Mayle FE, Walker JH, Soto JD, Iriarte J. 2014. Pre-Columbian raised-field agriculture and land use in the Bolivian Amazon. The Holocene 24: 231-241.

Wilding LP, Dress LR. 1983. Spatial variability and pedology. *In:* Wilding LP, Smeck N, Hall, GH (Eds Pedogenesis and Soil Taxonomy. I concepts and interactions, pp. 83-116. Elsevier. Amsterdam.

Wilson C, Simpson IA, Currie EJ. 2002. Soil management in pre-Hispanic raised field systems: micromorphological evidence from Hacienda Zuleta, Ecuador. *Geoarchaeology,* **17**: 261–283.

Woods WI, McCann JM. 1999. The anthropogenic origin and persistence of Amazonian Dark Earths. Yearbook Conference of Latin Americanist Geographers **25**: 7-14.

Woods WI,Glaser B. 2004. Towards an understanding of Amazonian Dark Earths. *In:* Glaser B, Woods WI (Eds.). Amazonian Dark Earths: Explorations in Space and Time, pp. 1-8. Springer, Heidelberg.

Zucchi A, Denevan WM. 1979. Campos elevados e historia cultural prehispanica en los llanos occidentales de venezuela. Universidad Católica Andrés Bello. Montalban (Caracas) **9**: 565-736.

Supplemental material (Tables S5.1- S5.6)

Table S5.1. Main physicochemical properties of the soils from the transect Mamoré-San Borja

Horizon	Depth (cm)	pH 1/2.5	E.C. 1/5 (dS/m)	Text. Class USDA	Sand			Silt	Clay	O.C. %	P Olsen mg/kg
					Coarse	Fine	Total				
					------------------------- % -------------------------						
Landform:		Mamoré floodplain									
Vegetable/land use:		Forest									
MOX-19/3	1-35	-	-	-	-	-	-	-		-	-
MOX-19/3	35-60	5.4	0.06	SL	0.0	69.3	69.3	20.6	10.1	0.3	15
MOX-19/4	60-75	5.8	0.06	SL	0.0	69.7	69.7	21.9	8.4	0.3	-
MOX-19/5	75-120	6.1	0.09	SiL	0.0	33.1	33.1	53.7	13.2	0.5	-
MOX-19/6	120-130	6.5	0.04	S	0.0	90.4	90.4	7.0	2.6	0.1	-
Landform:		Tinamuchi levee									
Vegetable/land use:		Gallery forest (*monte inundable*)									
MOX-20/2	2-4	4.7	0.21	SiC	0.1	3.9	4.0	40.1	56.0	4.7	9
MOX-20/3	4-30	4.4	0.09	SiC	0.2	2.8	3.0	55.4	41.8	1.0	4
MOX-20/4	30-45	4.7	0.06	C	0.1	3.9	4.0	43.1	52.9	0.7	1
MOX-20/5	45-75	5.3	0.06	C	0.2	2.8	3.0	38.4	58.9	-	1
MOX-20/6	75-90	5.4	0.08	C	0.1	3.9	4.0	36.1	60.2	-	1
MOX-20/7	90-125	5.2	0.09	CL	0.0	1.3	1.3	22.8	75.9	-	1
Landform:		Outer (higher) part of a dry lake									
Vegetable/land use:		Forest non flooded									
MOX-18/2	2-25	5.1	0.11	C	0.0	1.2	1.2	14.4	84.4	2.8	2
MOX-18/3	25-40	4.7	0.11	C	0.0	1.0	1.0	7.7	91.3	1.7	1
MOX-18/4	40-80	4.7	0.12	C	0.0	1.0	1.0	4.9	94.1	1.7	1
MOX-18/5	80-110	5.2	0.17	C	0.0	1.0	1.0	11.9	87.2	1.0	1
MOX-18/6	110-125	5.6	0.20	C	0.1	1.6	1.7	18.0	80.3	0.8	1
Landform:		Dry lake									
Vegetable/land use:		Pasture (*paja brava*)									
MOX-17/2	1-10	5.9	0.14	C	1.7	12.3	14.0	24.4	61.6	3.1	5
MOX-17/3	10-50	5.3	0.09	C	0.1	7.4	7.5	11.9	80.6	1.7	1
MOX-17/5	70-125	5.9	0.09	C	0.2	1.8	2.0	26.5	71.7	0.5	1
Landform:		Basin									
Vegetable/land use:		MiXed forest									
MOX-21/2	2-25	5.2	0.13	C	0.0	9.9	9.9	25.6	64.5	3.0	15
MOX-21/3	25-40	5.5	0.15	C	0.4	7.1	7.5	22.4	70.1	-	-
MOX-21/4	40-60	6.3	0.06	C	0.0	35.0	35.0	24.0	41.0	0.5	-
MOX-21/5	60-100	6.9	0.07	C	0.3	16.6	16.9	24.9	58.2	0.5	-
MOX-21/6	100-120	7.3	0.06	CL	0.0	34.3	34.3	33.5	32.2	0.3	-

E.C.: electrical conductivity relation soil/distilled water;: Textural classes: SL: sandy loam; SiL: silt loam; S: sandy, C: Clay; CL: Clay Loam; SiCL: silty clay loam; SiC: silty clay; L: loam; Size limits of USDA, diameter in mm: sand (2.0-0.05): coarse sand (2.0-0.25) fine sand (0.25-0.05) ; silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; P: phosphorus by method Olsen.

Table S5.1. Main physicochemical properties of the soils from the transect Mamoré-San Borja (cont.)

Horizon	Depth (cm)	pH 1/2.5	E.C. 1/5 (dS/m)	Text. Class USDA	Sand Coarse	Sand Fine	Sand Total	Silt	Clay	O.C. %	P Olsen mg/kg
					%						
Landform:		Basin									
Vegetable/land use:		Pasture									
MOX-16/2	1-21	5.1	0.07	SiC	0.0	32.8	32.8	50.7	16.5	1.1	4
MOX-16/3	21-40	5.9	0.80	CL	0.1	24.1	24.5	46.7	29.1	0.3	1
MOX-16/4	40-58	6.7	0.09	SiCL	1.6	8.3	9.9	50.8	39.3	0.3	1
MOX-16/5	58-85	7.1	0.15	CL	0.3	19.9	20.2	46.7	33.1	0.4	1
MOX-16/6	85-110	6.7	0.31	C	0.3	18.8	19.1	39.5	41.4	0.2	1
Landform:		Basin									
Vegetable/land use:		Forest (*monte alto*)									
MOX-15/3	2-12	4.9	0.19	C	0.1	7.4	7.5	37.4	55.1	2.7	9
MOX-15/4	12-27	5.3	0.09	C	0.3	6.6	6.9	30.4	62.7	1.3	5
MOX-15/5	27-41	5.1	0.08	C	0.4	1.2	1.6	12.1	86.3	1.0	1
MOX-15/6	41-50	5.1	0.05	C	0.2	12.6	12.8	25.2	62.0	-	-
MOX-15/7	50-70	5.6	0.04	SiCL	0.3	8.7	9.0	58.8	32.2	-	-
MOX-15/8	70-110	5.6	0.05	SiCL	0.3	9.3	9.6	54.5	35.9	-	-
Landform:		Basin									
Vegetable/land use:		Salitral sparse forest									
MOX-22/1	0-20	7.5	0.16	L	0.1	37.3	37.4	41.6	21.0	1.2	6
MOX-22/2	20-40	8.2	0.25	CL	0.2	20.6	20.8	46.4	32.8	0.4	2
MOX-22/3	80-100	7.8	1.31	L	0.2	39.7	39.9	33.7	26.5	-	-
MOX-22/4	100-120	8.2	1.30	CL	0.1	33.0	33.1	36.8	30.1	0.3	-
Landform:		Basin									
Vegetable/land use:		Forest. *Monte inundable*									
MOX-14/2	1-20	4.7	0.12	SiCL	0.0	9.0	9.0	53.6	37.4	3.3	7
MOX-14/3	20-50	5.2	0.11	SiCL	0.0	11.9	11.9	52.6	35.5	2.4	7
MOX-14/4	50-80	5.4	0.08	SiC	0.0	7.8	7.8	50.0	42.2	0.8	-
MOX-14/5	80-100	5.8	0.13	SiCL	0.2	6.3	6.5	50.2	43.3	0.5	-
MOX-14/6	100-130	5.6	0.39	SiC	0.1	3.4	3.5	40.7	55.9	0.3	-
Landform:		Basin									
Vegetable/land use:		Pasture. Slash and burn forest									
MOX-23/1	0-15	5.2	0.06	CL	0.1	32.3	32.3	39.1	28.6	-	6
MOX-23/2	15-25	5.3	0.05	L	0.5	36.7	37.2	35.6	26.9	-	6
MOX-23/3	25-55	5.3	0.04	CL	0.1	44.1	44.2	28.8	27.0	-	2
MOX-23/4	55-65	5.6	0.03	L	0.3	37.0	37.3	36.4	26.3	0.4	2
MOX-23/5	65-85	5.6	0.04	L	0.3	34.3	34.6	38.6	26.8	0.3	3
MOX-23/6	85-120	5.9	0.04	C	0.3	16.8	17.1	34.1	48.8	0.3	3

E.C.: electrical conductivity relation soil/distilled water;: Textural classes: SL: sandy loam; SiL: silt loam; S: sandy, C: Clay; CL: Clay Loam; SiCL: silty clay loam; SiC: silty clay; L: loam; Size limits of USDA, diameter in mm: sand (2.0-0.05): coarse sand (2.0-0.25) fine sand (0.25-0.05) ; silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; P: phosphorus by method Olsen.

Table S5.1. Main physicochemical properties of the soils from the transect Mamoré-San Borja (cont.)

Horizon	Depth (cm)	pH 1/2.5	E.C. 1/5 (dS/m)	Text. Class USDA	Sand Coarse	Sand Fine	Sand Total	Silt	Clay	O.C. %	P Olsen mg/kg
					%						
Landform:		Levee									
Vegetable/land use:		Forest									
MOX-7/1	0-17	5.3	0.08	SiL	0.0	29.0	29.0	51.5	19.4	1.0	7
MOX-7/2	17-67	5.4	0.05	SiL	0.0	20.1	20.1	57.1	22.8	0.1	6
MOX-7/3	67-120	5.4	0.05	SiL	0.0	12.4	12.4	60.6	26.9	0.1	8
Landform:		Basin; near Cuberene river									
Vegetable/land use:		Herbaceous pasture									
MOX-8/1	0-10	4.9	0.12	C	0.0	1.2	1.2	30.9	67.9	5.9	12
MOX-8/2	10-20	5.6	0.06	C	0.0	3.2	3.2	38.7	58.0	0.8	3
MOX-8/3	20-30	5.2	0.07	C	0.0	0.8	0.8	30.4	68.9	2.4	5
MOX-8/4	30-50	5.3	0.08	C	0.0	5.4	5.4	31.1	63.6	0.6	2
MOX-8/5	50-60	5.6	0.07	CL	0.0	35.5	35.5	31.5	33.0	0.5	2
MOX-8/6	90-100	6.1	0.07	SCL	0.0	62.3	62.3	14.3	20.4	0.2	2
MOX-8/7	100-130	6.2	0.05	LS	0.0	84.8	84.8	7.5	7.7	-	5
Landform:		Basin; near Cuberene river									
Vegetable/land use:		Bare land. Near MOX-8									
MOX-9/1	0-10	4.8	0.09	C	0.0	2.1	2.1	34.4	63.5	1.9	13
MOX-9/2	10-20	5.2	0.18	C	0.0	0.9	0.9	33.3	65.8	4.9	13
MOX-9/3	20-40	5.2	0.10	SiC	0.0	1.3	1.3	40.3	58.5	1.2	9
MOX-9/4	40-45	5.3	0.14	C	0.0	1.9	1.9	14.9	83.3	0.6	3
MOX-9/5	45-60	6.1	0.09	C	0.0	2.6	2.6	38.6	58.8	0.5	3
MOX-9/6	60-80	5.7	0.09	C	0.1	1.0	1.1	29.6	69.3	0.5	4
MOX-9/7	80-90	5.8	0.09	C	0.0	0.4	0.4	35.1	64.5	0.5	4
MOX-9/8	90-120	5.8	0.13	SiC	0.1	1.0	1.1	41.7	57.2	0.5	3
Landform:		Levee									
Vegetable/land use:		Forest, *Loma*									
MOX-13/2	1-2	6.5	1.06	L	0.1	33.9	34.0	46.2	19.8	16.0	80
MOX-13/3	2-32	5.9	0.08	SL	0.2	53.4	53.6	35.6	10.9	1.2	30
MOX-13/4	32-40	5.6	0.07	L	0.2	46.8	47.0	40.4	12.6	0.5	51
MOX-13/5	40-72	6.3	0.05	L	0.6	39.6	40.2	42.3	17.5	0.4	66
MOX-13/6	72-120	6.1	0.04	L	0.1	37.4	37.5	46.2	16.3	0.2	93
Landform:		Basin									
Vegetable/land use:		Herbaceous pasture									
MOX-12/1	0-10	5.6	0.04	L	0.3	39.3	39.6	42.7	17.6	1.2	2
MOX-12/2	10-20	5.7	0.04	L	0.4	36.3	36.7	43.9	19.5	0.8	2
MOX-12/3	20-55	6.2	0.04	L	1.3	35.6	36.9	45.2	17.9	-	-
MOX-12/4	55-70	6.7	0.04	SiCL	1.1	18.2	19.3	49.4	31.3	-	-
MOX-12/4	70-120	7.1	0.08	SiC	0.0	10.8	10.8	40.8	48.4	-	-

E.C.: electrical conductivity relation soil/distilled water;: Textural classes: SL: sandy loam; SiL: silt loam; S: sandy, C: Clay; CL: Clay Loam; SiCL: silty clay loam; SiC: silty clay; L: loam; Size limits of USDA, diameter in mm: sand (2.0-0.05): coarse sand (2.0-0.25) fine sand (0.25-0.05) ; silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; P: phosphorus by method Olsen

Table S5.1. Main physicochemical properties of the soils from the transect Mamoré-San Borja (cont.)

Horizon	Depth (cm)	pH 1/2.5	E.C. 1/5 (dS/m)	Text. Class USDA	Sand			Silt	Clay	O.C %	P Olsen mg/kg
					Coarse	Fine	Total				
					%						
Landform:		Levee. Maniqui river									
Vegetable/land use:		Forest gallery. *Monte inundable*									
MOX-11/2	2-25	5.9	0.12	SiL	0.0	33.4	33.4	51.4	15.2	0.7	13
MOX-11/3	25-40	6.2	0.06	SL	0.0	59.7	59.7	32.8	7.5	0.3	10
MOX-11/4	40-70	5.4	0.07	SiL	0.0	17.9	17.9	63.7	18.4	0.5	-
MOX-11/5	70-100	5.4	0.07	L	0.0	51.9	51.9	37.5	10.6	0.2	-
MOX-11/6	100-130	5.3	0.07	L	0.0	42.5	42.5	44.0	13.6	0.2	-

E.C.: electrical conductivity relation soil/distilled water;: Textural classes: SL: sandy loam; SiL: silt loam; S: sandy, C: Clay; CL: Clay Loam; SiCL: silty clay loam; SiC: silty clay; L: loam; Size limits of USDA, diameter in mm: sand (2.0-0.05): coarse sand (2.0-0.25) fine sand (0.25-0.05) ; silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; P: phosphorus by method Olsen

Table S5.2. Cation Exchange characteristics from soil of the transect Mamoré-San Borja

Horizon	Depth cm	CEC	Ca^{2+}	Mg^{2+}	K^{+}	Al^{3+}	ECEC*	V* %	∑Cat/ECEC*	Al^{3+}/ECEC*
		------------------------ cmol+/kg ------------------------								
MOX-20/2	2-4	28.8	9.5	3.1	0.50	2.66	15.76	45.49	0.83	0.17
MOX-20/3	4-30	18.4	3.9	1.1	0.29	6.48	11.77	28.75	0.45	0.55
MOX-20/4	30-45	21.7	3.6	0.5	0.25	11.68	16.03	20.05	0.27	0.73
MOX-20/5	45-75	23.4	5.3	0.6	0.32	11.63	17.85	26.58	0.35	0.65
MOX-20/6	75-90	27.2	7.5	1.1	0.33	9.5	18.43	32.83	0.48	0.52
MOX-20/7	90-125	33.5	10.7	1.7	0.34	9.2	21.94	38.03	0.58	0.42
MOX-18/2	2-25	30.1	11.8	5.2	0.54	2.22	19.76	58.27	0.89	0.11
MOX-18/3	25-40	33.1	9.1	4.5	0.55	6.96	21.11	42.75	0.67	0.33
MOX-18/4	40-80	41.4	7.7	3.7	0.47	8.23	20.10	28.67	0.59	0.41
MOX-18/5	80-110	32.3	15.2	5.4	0.48	2.46	23.54	65.26	0.90	0.10
MOX-18/6	110-125	26.4	15.8	5.2	0.41	0.39	21.8	81.10	0.98	0.02
MOX-17/2	1-10	24.1	16.1	3.4	0.19	0.12	19.81	81.70	0.99	0.01
MOX-17/3	10-50	25.9	10.3	4.6	0.41	3.84	19.15	59.11	0.80	0.20
MOX-17/5	70-125	23.2	16.8	6.3	0.34	0.27	23.71	101.03	0.99	0.01
MOX-16/2	1-21	12.5	3.1	0.7	0.13	1.06	4.99	31.44	0.79	0.21
MOX-16/3	21-40	14.2	4.7	2.1	0.22	2.36	9.38	49.44	0.75	0.25
MOX-16/4	40-58	19.4	10.1	4.9	0.35	0.10	15.45	79.12	0.99	0.01
MOX-16/5	58-85	14.6	9.5	4.0	0.25	0.08	13.83	94.18	0.99	0.01
MOX-16/6	85-110	17.7	11.7	4.8	0.29	0.1	16.89	94.86	0.99	0.01
MOX-23/1	0-15	11.4	4.4	1.5	0.14	0.55	6.59	52.98	0.92	0.08
MOX-23/2	15-25	11.7	3.9	1.8	0.19	1.12	7.01	50.34	0.84	0.16
MOX-23/3	25-55	9.6	3.2	1.9	0.18	1.77	7.05	55.00	0.75	0.25
MOX-23/4	55-65	10.4	3.6	2.2	0.17	1.08	7.77	57.40	0.77	0.23
MOX-23/5	65-85	10.9	2.5	3.8	0.19	1.64	8.13	59.54	0.80	0.20
MOX-23/6	85-125	18.6	8.4	6.3	0.39	1.29	16.38	81.13	0.92	0.08

CEC: capacity exchange cation; Ca^{2+}: calcium; Mg^{2+}: magnesium;; K^{+}: potassium; Al^{3+}: Aluminum; ECEC: effective cation exchange capacity; V: base saturation. ∑Cat.: sum of cations

*The calculations do not consider sodium (Na^{+})

Table S5.2. Cation Exchange characteristics from soil of the transect Mamoré-San Borja (cont.)

Horizon	Depth cm	CEC	Ca^{2+}	Mg^{2+}	K^{+}	Al^{3+}	ECEC*	V* %	∑Cat/ECE*C	Al^{3+}/ECEC*
		------------------------ cmol+/kg ------------------------								
MOX-7/1	0-17	11.7	6.80	1.78	0.21	0.34	9.13	75.13	0.96	0.04
MOX-7/2	17-67	13.6	4.50	2.33	0.20	2.78	9.81	51.69	0.72	0.28
MOX-7/3	67-120	16.5	5.60	3.13	0.29	3.24	12.26	54.67	0.74	0.26
MOX-8/1	0-10	38.8	2.34	0.20	0.10	0.42	3.06	6.80	0.67	0.11
MOX-8/3	20-30	27.5	1.91	0.30	0.13	0.46	2.80	8.51	0.84	0.16
MOX-8/4	30-50	25.8	1.69	0.74	0.40	0.45	3.28	10.97	0.41	0.07
MOX-8/5	50-60	13.7	4.60	0.71	0.16	1.65	7.12	39.93	0.77	0.23
MOX-8/6	90-100	7.3	4.10	0.58	0.12	0.79	5.59	65.75	0.86	0.14
MOX-8/7	100-130	2.5	1.40	0.21	0.03	0.23	1.87	65.60	0.88	0.12
MOX-9/1	0-10	25.5	10.10	3.07	0.47	3.37	17.01	53.49	0.80	0.20
MOX-9/2	10-20	34.3	13.10	3.40	0.71	2.79	20.00	50.17	0.86	0.14
MOX-9/3	20-40	16.5	4.30	1.28	0.23	3.32	9.13	35.21	0.64	0.36
MOX-9/4	40-45	38.4	17.80	6.67	0.55	2.99	28.01	65.16	0.89	0.11
MOX-9/5	45-60	26.9	14.10	4.39	0.41	1.26	20.16	70.26	0.94	0.06
MOX-9/6	60-80	28.9	14.30	4.83	0.59	2.16	21.88	68.24	0.90	0.10
MOX-9/7	80-90	22.8	11.20	3.98	0.50	2.55	18.23	68.77	0.86	0.14
MOX-9/8	90-120	20.9	10.80	3.83	0.37	1.20	16.20	71.77	0.93	0.07
MOX-13/2	1-2	-	-	-	1.90	-	-	-	-	-
MOX-13/3	2-32	-	-	-	0.15	0.10	0.25	-	0.60	0.40
MOX-13/4	32-40	8.7	5.80	0.70	0.13	0.13	6.76	76.21	0.98	0.02
MOX-13/5	40-72	7.3	8.50	0.90	0.18	0.11	9.69	131.23	0.99	0.01
MOX-13/6	72-120	10.1	7.20	0.80	0.21	0.29	8.50	81.29	0.97	0.03

CEC: capacity exchange cation; Ca^{2+}: calcium; Mg^{2+}: magnesium;; K^{+}: potassium; Al^{3+}: Aluminum; ECEC: effective cation exchange capacity; V: base saturation. ∑Cat.: sum of cations

*The calculations do not consider sodium (Na^{+})

Table S5.3. Main physicochemical properties of the slash and burn soils (*chacos*)

Horizon	Depth (cm)	pH 1/2.5	E.C. 1/5 (dS/m)	Text. Class USDA	Sand			Silt	Clay	O.C %	Nt %	C/N	P Olsen mg/kg
					Coarse	Fine	Total						
					%								
MOX-26/2	1-3	5.8	0.14	SL	0.0	59.96	59.96	29.31	10.73	4.0	0.33	12.1	25.0
MOX-26/3	3-30	5.5	0.07	SL	0.0	63.93	63.93	27.26	8.81	1.1	0.10	10.5	7.3
MOX-26/4	30-100	5.6	0.03	SL	0.1	66.26	66.36	21.58	12.06	0.3	-	-	-
MOX-29/2	2-20	5.7	0.10	L	0.1	39.88	39.98	48.16	11.86	1.1	-	-	8.3
MOX-29/3	20-40	5.1	0.06	SiL	0.0	34.57	34.57	50.61	14.82	0.5	0.05	10.5	3.8
MOX-30/1	0-20	5.7	0.14	SiL	0.0	32.20	32.20	53.90	13.90	1.5	-	-	12.0
MOX-30/2	20-40	5.4	0.06	SiL	0.0	32.89	32.89	50.47	16.64	0.5	0.05	10.1	6.4
MOX-31/1	0-20	6.3	0.06	SL	0.0	57.30	57.30	31.40	11.10	0.5	0.06	7.8	2.0
MOX-31/2	20-40	6.5	0.13	SL	0.0	59.40	59.40	29.50	11.10	1.4	0.15	9.3	6.0
MOX-32/2	20-40	5.3	0.08	SiL	0.0	26.60	26.60	59.00	14.30	1.1	0.15	7.4	7.0
MOX-33/3	20-30	5.5	0.08	SiL	0.6	22.90	22.90	58.20	18.30	0.6	0.06	10.7	3.0
MOX-34/1	0-20	5.7	0.09	SiL	2.3	11.31	13.59	59.78	26.63	1.1	0.12	9.2	20.0
MOX-34/2	20-40	5.4	0.07	SiCL	2.3	9.19	11.49	55.70	32.81	0.6	0.08	8.0	8.7

E.C.: electrical conductivity relation soil/distilled water;: Textural classes: SL: sandy loam; SiL: silt loam; L: Loam; CL: Clay Loam; SiCL: silty clay loam; Size limits of USDA, diameter in mm: sand (2.0-0.05): coarse sand (2.0-0.25) fine sand (0.25-0.05) ; silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; C/N: ratio: carbon/total nitrogen; C : considering 57% of organic matter; P: phosphorus by method Olsen

Table S5.4. Micromorphological pedofeatures of raised field MOX-6 ridge and channel

Reference	Side/ position	Genetic horizon	Depth cm	Clay illuviation and carbonate redistribution[a]		Redoximorphic features[b]		Biological activity class[d,e]
				Pedofeatures	Class[d]	Pedofeatures	Class[c]	
6/1	Side 2 Ridge	A	0-17	None	-	Impregnative orthic nodules, hypocoatings in active pores	B-C	+++
6/2		Ag_3	17-33	Very few anisotropic coatings of clay and silt around pores, fine (<100 μm)	+	Abundant typic impregnative nodules, orthic and anorthic, few impregnative quasicoatings	C	+++
6/3		Btg_1	44-54	Common anisotropic coatings of clay and silt around pores, fine (<100 μm) Common clay and silt intercalation	++	Abundant typic impregnative nodules, orthic and disorthic, due to slickensides	B	+++
6/4		Btg_2	85-95	Common, very fine microlaminated coatings of clay (<50 μm) Few clay and silt intercalation	++	Abundant typic impregnative nodules, orthic, some clay and iron-depletion hypocoatings around pores	B-C	+++
6/5	Side 1 Ridge	Nest (Btg_1)	48-60	Frequent compound coatings of anisotropic clay to fine sand (<200 μm)	+++	Abundant typic impregnative nodules, orthic and disorthic, impregnative hypo- and quasicoatings.	C	+
6/6	Side 3 Channel	A_1	0-10	None	-	Few hypocoatings around roots, orthic nodules.	B	++
6/7		A_2	12-32	Very few anisotropic coatings of clay and silt	+	Abundant hypocoatings around roots, depleted groundmass	F	++
6/8		A_3	38-47	Frequent compound coatings and intercalations of anisotropic clay to fine sand (<200 μm)	+++	Very abundant hypo- and quasicoatings in vughs and biopores; frequent anorthic nodules, some fragmented	E-F	++

[a] Carbonates only present when specified in the table. [b] Fe oxi-hydroxides, unless otherwise indicated. [c] A (slight hydromorphism) to G (strong hydromorphism) according to Lindbo *et al.* (2010).[d] None or rare (-), Few (+), Common (++), Frequent (+++). [e] Faunal channels and excrement infillings

Table S5.5. Micromorphological pedofeatures of raised field MOX-3 (equivalent natural site)

Reference	Side/ position	Genetic horizon	Depth cm	Clay illuviation and carbonate redistribution[a]		Redoximorphic features[b]		Biological activity class[d,e]
				Pedofeatures	Class[d]	Pedofeatures	Class[c]	
3/1		A_1/A_2	1-21	Clay intercalations	-	Very abundant hypocoatings, few quasicoatings, few anorthic nodules, some fragmented	C	++
3/2		Btg_1 / Btg_2	21-51	Clay intercalations and fragmented anisotropic coatings of clay and silt	++	Orthic nodules, some Fe-depletion hypocoatings	B–D (lower part)	+++
3/3		Btg_3	51-56	Clay intercalations and fragmented anisotropic coatings of clay and silt. Orthic carbonate nodules and infillings, micritic and sparitic.	++	Orthic nodules, Fe and clay depletion hypocoatings. Fragment of Mn-oxide coating.	B with a part G	++
3/4		$2Btg_4$	107-123	Sedimentary material, coatings of clay and silt, some of them anisotropic	+	Orthic nodules	A-B	+
3/5		$2Btg_5$	130-157	Sedimentary material, coatings of clay and silt, some of them anisotropic. Orthic carbonate nodules and infillings, micritic and sparitic.	++	Orthic nodules	A-B	++

[a] Carbonates only present when specified in the table. [b] Fe oxi-hydroxides, unless otherwise indicated. [c] A (slight hydromorphism) to G (strong hydromorphism) according to Lindbo *et al.* (2010). [d] None or rare (-), Few (+), Common (++), Frequent (+++). [e] Faunal channels and excrement infillings

Table S5.6. Micromorphological pedofeatures of raised field MOX-51

Reference	Side/ position	Genetic horizon	Depth cm	Clay illuviation and carbonate redistribution[a]		Redoximorphic features[b]		Biological activity class[d,e]
				Pedofeatures	Class[d]	Pedofeatures	Class[c]	
51-1/6	Side 1 Ridge	A_2	10-20	Very few intercalations and dusty coatings around pores	-	Few rounded orthic and disorthic nodules	B	+++
51-1/5		Bt_2	55-65	Frequent anisotropic clay and silt coatings. Few clay intercalations.	++	Few rounded orthic and disorthic nodules	B	++
51-1/4		$3Bt_3$	92-102	Frequent compound coatings of silt and clay. Frequent clay intercalations.	+++	Fragmented orthic nodules, hypo- and quasicoatings around pores.	E	+++
51-1/1		3Assb	130-144	None	-	Quasicoatings and orthic nodules	E	++
51-1/2		$3Btgb_1$	144-153	Some anisotropic, deformed clay and fine silt coatings around the Fe-hypocoatings	+	Hypocoatings and Fe-depleted groundmass	F	+++
51-1/3		$4Btgb_2$	153-166	Some anisotropic, deformed clay and fine silt coatings around the Fe-hypocoatings	+	Hypocoatings and Fe-depleted groundmass	F	++
51-3/1	Side 2 Channel	A_2	22-32	Slightly deformed, microlaminated clay coatings around pores.	+	Fe-depleted hypocoatings and orthic nodules	D-E	++
51-3/2		$2Btg_2$	46-56	Abundant anisotropic clay and fine silt coatings around pores and coarse fragments	+++	Fe-depleted hypocoatings and orthic nodules	D-E	+++
51-3/3		$4Btgb_2$	130-147	Frequent anisotropic clay and fine silt coatings around pores and coarse fragments	++	Heterogeneous material due to mixing, with features of all classes.	-	+++

[a] Carbonates only present when specified in the table. [b] Fe oxi-hydroxides, unless otherwise indicated. [c] A (slight hydromorphism) to G (strong hydromorphism) according to Lindbo *et al.* (2010).[d] None or rare (-), Few (+), Common (++), Frequent (+++). [e] Faunal channels and excrement infillings

Table S5.7. Micromorphological pedofeatures of site MOX- 99-3 (ridge) and raised field MOX-99-8

Reference	Side/ position	Genetic horizon	Depth cm	Clay illuviation and carbonate redistribution[a]		Redoximorphic features[2]		Biological activity class[d,e]
				Pedofeatures	Class[d]	Pedofeatures	Class[c]	
99-3/4	Side 1 Ridge	Bwkc	37-50	Microlaminated clay coatings and intercalations, Micrite hypocoatings and nodules, sparite infillings.	+++	Few orthic and anorthic nodules	B	++ Phytoliths
99-3/1	Side 3	$Bwkn_2$	87-100	Compound coatings of clay, silt and fine sand. Hypocoatings of $CaCO_3$.	++	Orthic nodules and small anorthic nodules	B	++
99-3/3		C VI	166-177	None (structureless quartz sand)	-	Very few orthic nodules	B	-
99-3/2		Akcb	187-197	Compound coatings of clay, silt and fine sand. Micrite hypocoatings and sparite infillings.	++	Orthic nodules and Fe-depleted hypocoatings	D	+++
99-8/4		A_2	11-27	Frequent microlaminated clay coatings, fragments of sedimentary material	+++	Orthic and disorthic nodules, some Fe-depletion hypocoatings	B-C	+++
99-8/3		Btg_1	27-46	Frequent compound clay+silt(+fine sand) and microlaminated clay coatings; clay intercalations	+++	Orthic and disorthic nodules, hypocoatings covered by clay coatings	C	++
99-8/2		Btg_2	60-80	Frequent microlaminated clay coatings	+++	Large orthic nodules, strongly impregnated	B	++
99-8/1		$2Cg_1$	85-102	Common anisotropic clay and silt coatings	++	Orthic nodules, hypocoatings covered by clay coatings and Fe-depletion hypocoatings	C-D	+
99-8/10	Side 3 Channel	A_2	7-20	None	-	Hypocoatings and orthic nodules, moderately impregnated	C	++
99-8/9	Channel	Btg_1	20-40	Few clay intercalations	+	Frequent hypocoatings and nodules, Fe-depleted groundmass	F-G	+++
99-8/8		Btg_2	40-63	Common compound clay to fine sand coatings and very fine microlaminated clay coatings	++	Large orthic nodules, strongly impregnated and fragmented by fauna; Fe-depleted hypocoatings	C	+++
99-8/7		$2Cg_1$	85-102	Few coatings of clay and silt	+	Large orthic nodules, moderately impregnated	B	+

[a] Carbonates only present when specified in the table. [b] Fe oxi-hydroxides, unless otherwise indicated. [c] A (slight hydromorphism) to G (strong hydromorphism) according to Lindbo *et al.* (2010).[d] None or rare (-), Few (+), Common (++), Frequent (+++). [e] Faunal channels and excrement infillings

Table S5.8. Supplementary information

MOX-26 counter part of MOX-99/3. Levee. Forest (*monte lavadero*). Near Curebere river

Horizon	Depth (cm)	Genetic horizon	Mottles	pH 1/2.5	E.C. 1/5 (dS/m)	Text. Class USDA	Sand			Silt	Clay	O.C.	P Olsen
							Coarse	Fine	Total			%	mg/kg
							%						
Landform:	Levee												
Vegetable/land use:	Forest (*monte lavadero*)												
MOX-26/1	1-3	A_1	No	5.8	0.14	SiL	0.0	60.0	60.0	29.3	10.7	4.0	25
MOX-26/2	3-30	A_2	No	5.5	0.07	SiL	0.0	63.9	63.9	27.3	8.8	1.0	7
MOX-26/3	30-100	B	Few	5.6	0.03	SiL	0.1	66.2	66.3	21.6	12.1	0.3	-

E.C.: electrical conductivity relation soil/distilled water;: Textural class: SiL: silt loam; Size limits of USDA, diameter in mm: sand (2.0-0.05): coarse sand (2.0-0.25) fine sand (0.25-0.05) ; silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; P: phosphorus by method Olsen

Table S5.9. Supplementary information MOX-55. Former Levee

Morphological properties of MOX-55. Equivalent natural soil (MOX-51)

Genetic horizon	Depth cm	Munsell colour (moist.)	Soil structure	Mottling		Artifacts/ charcoal	Remarks
				Amount	Colour		
A_1	0-2	10 YR 2/2	sab	no	-	-	-
A_2	2-12	10 YR 4/2	sab	no	-	-	-
A_3	12-23	10 YR 5/2	sab	no	-	-	-
Btg_1	23-43	7.5 YR 6/4	sab	few	10 YR 2/2	-	Clay skin in peds faces Fe and Mn pisolits
Btg_2	43-78	7.5 YR 8/1 (ped face) 7.5 YR 4/6 (inside face)	blocky	many	7.5 YR 8/1	-	
$2Btg_3$	78-140	7.5 YR 8/1 (ped face) 7.5 YR 4/6 (inside face)	blocky	many	7.5 YR 8/1	-	
3C (sand)	140-160	-	struct unless	no	-	-	

sab: subangular blocky

Table S5.10: Complementary data MOX-55. Natural soil *Estancia* Moxitania (*Monte alto lavadero*) Pasture after slash and burn a forest (like MOX-51)

Genetic horizon	Depth cm	pH 1/2.5	E.C. 1/5 (dS/m)	Text. Class USDA	Sand	Silt	Clay	O.C. %	P Olsen mg/kg	CEC	Ca^{2+}	Mg^{2+}	K^+	Na^+	V %
					%					cmol+/kg					
A_1	0-2	6.8	0.37	SiL	15.6	67.7	16.7	2.7	31	-	-	-	-	-	-
A_2	2-12	6.3	0.14	SiL	16.9	69.4	13.7	1.0	4	7.6	3.5	1.7	0.14	0.10	71.7
Btg_1	23-43	5.5	0.14	SiCL	9.0	64.1	26.9	0.3	2	12.4	3.4	3.3	0.13	0.15	56.3
Btg_2	43-78	5.6	0.12	SiCL	7.8	65.2	27.0	0.2	4	14.9	4.5	4.8	0.12	0.20	64.5
$2Btg_3$	78-140	5.7	0.10	SiL	26.6	52.9	20.5	0.2	4	11.4	3.5	4.7	0.10	0.21	76.4
3C	140-160	7.3	0.12	S	91.8	5.9	2.3	0.1	6	2.0	1.2	0.7	0.03	0.01	98.0

E.C.: electrical conductivity relation soil/distilled water;: Textural classes:SiL: silt loam; S: sandy;SiCL: silty clay loam; Size limits of USDA, diameter in mm: sand (2.0-0.05); silt (0.05-0.002); clay (<0.002); O.C.: organic carbon; P: phosphorus by method Olsen; CEC: capacity exchange cation; Ca^{2+}: calcium; Mg^{2+}: magnesium; K^+: potassium; V: base saturation

CAPÍTOL 6:

Discussió i conclusions

6.1. Discussió

La recerca que es presenta en aquesta tesi es deriva de les activitats de cartografia de sòls que l'autor ha desenvolupat al llarg d'aquests anys. S'ha treballat fonamentalment a Catalunya, però també en altres indrets, com per exemple *Llanos* de Moxos (Bolívia), on s'han realitzat estudis de sòls. Amb aquesta investigació es vol donar una resposta coherent a algunes de les moltes preguntes que han sorgit en la realització d'aquests treballs.

6.1.1. La coberta edàfica i el material originari

La coberta edàfica forma un continu que, per a la seva comprensió, s'intenta compartimentar, per exemple, quan s'elaboren mapes de sòls a qualsevol escala. Seguint el model clàssic establert per Jenny (1941), un aspecte bàsic és dilucidar el material originari del sòl.

Els processos geogènics són sovint aquells que han donat lloc al material originari o l'han modificat en unes condicions que hom podria anomenar no edafogèniques, malgrat que autors com Phillips (2004) alerten del risc d'aquestes distincions. Els loess constitueixen un cas molt especial de processos geogènics que s'han estudiat en un dels articles (Boixadera *et al.,* 2015).

6.1.1.1. Loess

En els darrers anys, i des del treball de Yaalon *et al.* (1973), ha aparegut un nombre creixent d'evidències del paper que tenen els materials eòlics en la formació dels sòls. Així Yaalon (1987) destaca el paper de les aportacions eòliques en la gènesi dels sòls a la Conca Mediterrània. A més, proposa uns llindars perquè aquestes aportacions eòliques es puguin reflectir a la (macro)morfologia dels sòls. La seva proposta estableix que per sota de 50 g/m^2/any no es produeixen formacions loèssiques, perquè s'incorporen al sòl i no en formen dipòsits. L'exemple de la Conca Mediterrània és un cas clar de com aquestes aportacions determinen la morfologia del sòl. Aquest fet s'il·lustra de manera fefaent a Boixadera *et al.* (2015).

El concepte de loess encabeix diferents aspectes que, des del punt de vista de la coberta edàfica, cal destacar. Un d'ells és la naturalesa eòlica del seu transport i deposició; l'altra és que els materials que anomenem loess pateixen simultàniament un procés edàfic que els dóna una aparença característica (color, estabilitat, etc…) i els diferencia clarament dels dipòsits derivats i/o barrejats dels loess. A aquests darrers, per a una millor comprensió i simplicitat, s'anomenaran *loess-like*.

A Catalunya, per buscar un marc geològic concret, la influència dels materials eòlics en els sòls no ha merescut l'atenció que el treball de Boixadera *et al.* (2015) demostra que tenen. Geòlegs com Solé Sabarís (1946) ja fan esment de l'existència d'aquests materials en diferents indrets i, en alguns d'aquests (Cardener, Manresa) s'ha pogut constatar la precisió de les seves observacions. Malgrat això, aquests materials desapareixen a la pràctica, i durant molts anys, també en la literatura i cartografia geològica i edafològica. Tanmateix, les referències bibliogràfiques que apareixen són imprecises i escasses.

Autors estrangers, particularment alemanys (Brunnacker, 1969), referencien aquests dipòsits a diferents indrets de Catalunya en nombroses ocasions. Un reconeixement personal de les àrees en què han estat citats revela que, ni de bon tros, és sempre evident la presència d'aquests materials, fet que indicaria una certa tendència a identificar com a loess o *loess-like* qualsevol material llimós i groguenc o rubefactat i sense elements grossos, amb independència de la seva posició geomorfològica o, en altres paraules, independentment que puguin existir altres processos que expliquin el dipòsit.

Dels treballs en què ha participat l'autor i com a hipòtesi de treball, es creu que existeixen a Catalunya més dipòsits de loess dels que comunament s'accepta (Manlleu, San Pere de Ribes, Bescanó,…) (Mücher *et al*., 1990). A més, aquests formen una coberta molt discontínua, que s'ha conservat (o només s'havia dipositat) en posicions geomorfològiques particulars (e.g. a sotavent, com a Almenara). En molts indrets, aquesta coberta era tan prima que s'ha erosionat o bé l'acció antròpica (treball del sòl, abancalament com a La Granadella) l'ha fet desaparèixer. Malgrat això, només una explicació de quins han estat els mecanismes que determinen el dipòsit d'aquests materials pot ajudar a modelitzar les àrees on es localitzen.

Aquests loess es datarien d'entre uns 17 i 34.000 anys BP o més antics (Boixadera et al. 2015). Els dipòsits més antics que es poden identificar com a loess són molt escassos; és el cas de Mas de l'Alerany, amb més de 115.000 anys BP, probablement 130.000 anys BP.

Els loess objecte de la investigació d'aquesta tesi es caracteritzen per ser de granulometria més arenosa que la d'altres indrets del món, comparables en aquest sentit amb els de Matmata (Tunísia) (Coudé-Gaussen *et al.,* 1983).També són molt rics en carbonats i presenten acumulacions de guix.

Els loess a la part oriental de la Depressió de l'Ebre (Serra d'Almenara) es diferencien clarament d'altres dipòsits llimosos, que en diferents indrets de la Vall de l'Ebre han estat anomenats llims guixencs i se'ls ha atribuït un origen eòlic (Riba *et al*., 1962). Així, la recerca edafològica i geomorfològica (Herrero *et al*., 1992; Artieda, 1996; Poch, 1992) ha posat reiteradament en evidència que el seu origen no és eòlic en un gran ventall de situacions. En qualsevol cas, i com ja s'ha dit abans, els dos tipus de dipòsits (els loess i els derivats de l'alteració del guix) són clarament diferents també en la seva localització espacial.

6.1.1.2. Altres aportacions eòliques

Seguint amb el model de les aportacions eòliques i la seva significació edàfica proposat per Yaalon (1987) cal fer esment a aquelles que per la seva quantitat són integrades dins de la morfologia del sòl. Aquest seria el cas dels sòls de l'Empordà (Boixadera *et al*., capítol 3) on aporten algunes claus sobre la seva gènesi i que d'alguna manera es poden fer extensives a altres sòls de Catalunya.

A l'Empordà, si hom admet que les aportacions eòliques en forma de pluges de fang es poden quantificar, encara que de forma aproximada, amb les dades d'Àvila *et al*. (1997) existeixen superfícies de sòls no calcàries on aquestes aportacions serien integrades al sòl sense deixar marques en la seva morfologia en forma d'acumulacions de carbonats.

Àvila *et al.* (1997, 2007) aporten una considerable quantitat d'informació sobre les aportacions eòliques a Catalunya. La situació més extrema seria la proposada per Muhs *et al.* (2010) que, pel cas de Mallorca, afirmen que la principal font de materials originaris és eòlica. Caldria admetre, i d'acord amb les idees de Yaalon (1987), que els materials transportats pel vent tenen importància significativa als nostres sòls: és el cas dels horitzons càlcics/petrocàlcics del Maresme, o el cas de l'elevada saturació de bases als sòls de granodiorites de Prades per posar un parell d'exemples.

En l'àmbit de la classificació de sòls, el fet de reconèixer que l'aportació de materials eòlics és un fenomen generalitzat a Catalunya, si més no fins a cotes de 1000 m (Prades, Montseny), permet respondre la qüestió que planteja *Soil Taxonomy* (SSS, 1975) a l'hora d'identificar un horitzó càmbic. La definició d'un horitzó càmbic en medis semiàrids en sòls amb carbonats o on els carbonats siguin aportats pel vent requereix identificar aquesta translocació al perfil (SSS, 1975; Smith, 1965). La manca de carbonats secundaris en molts casos indicaria, en aquests casos, l'absència d'un horitzó càmbic. Cal tenir en compte que això exclou que hi hagi hagut canvis en el color de l'horitzó B, una altra de les condicions alternatives que un horitzó B càmbic requereix.

Les aportacions eòliques serien útils també a l'hora d'explicar la formació d'horitzons (petro)càlcics on els balanços de carbonats no permeten explicar la seva gènesi in situ. Així, a les aportacions laterals (superficials o subsuperficials), caldria sumar-hi els inputs aeris. Així també, els carbonats dels perfils de la Serra d'Almenara (Agramunt, Lleida) podrien tenir un origen fonamentalment eòlic.

6.1.1.3 Aportacions per les aigües d'inundació a los Llanos de Moxos

Les aigües d'inundació que afecten als Llanos de Moxos constituirien un altre cas de processos geogènics. En aquest cas (Boixadera *et al.*, capítol 5), aporten sediments que s'integren ràpidament al sòl, entre els quals hi ha minerals d'argila diferents als dels ambients altament meteoritzats (Irion ,1993), a més de cations en solució. Això fa que l'acidificació d'aquests sòls sigui limitada, i els sòls que es desenvolupin es classifiquin com a Alfisòls.

6.1.2. El model sòl – paisatge

En la investigació duta a terme a l'Empordà (Boixadera *et al.*, en prep. a) el propòsit de la recerca era clarament acabar millorant el model sòl-paisatge existent. En la resta d'investigacions presentades en aquesta tesi el resultat final ha estat també en aquest sentit. El model sòl-paisatge, com va formular Hudson (1992), es la peça clau per l'elaboració dels mapes de sòls i per tant la seva millora comporta entre altres coses també un avenç significatiu en la millora de la cartografia que es pugui elaborar d'una zona.

La identificació dels loess com a material originari transportat pel vent constitueix un canvi notable en els models conceptuals a l'hora d'elaborar la cartografia de sòls, on aquests han estat descrits i estudiats (Boixadera *et al.*, 2015). Tot i que havien estat esmentats per altres autors (Iriondo *et al.*, 2007), ara es disposa d'una primera cartografia de l'àrea afectada. La seva influència afectaria l'elaboració del Mapa de Sòls de Catalunya, com a mínim, en dos punts particulars: la definició de les unitats taxonòmiques i la identificació de les discontinuïtats de la coberta edàfica, això és, a l'hora de posar els límits a les unitats cartogràfiques. Les unitats taxonòmiques (sèries) del Mapa de Sòls de Catalunya (ICC-DAR-IGC, 2010) definida com el nivell més baix dels sistemes taxonòmics (Boulaine, 1980) empren el material originari com un dels components de la seva definició i és per això que introduir els loess comporta afegir noves i diferents sèries de sòls. També a l'hora de delimitar els tipus de sòls existents en un edafopaisatge la seva delimitació té en compte l'origen (forma de dipòsit) d'aquests.

L'aprofundiment en el coneixement de les característiques i gènesi dels sòls de l'Empordà (Boixadera *et al*., en capítol 3) permet identificar alguns trets que són aplicables a l'esmentat model sòl – paisatge a l'hora d'aplicar-lo al seu entorn immediat, però també a altres àrees properes de clima i materials originaris comparables. Dels quatre sòls de referència estudiats, els de la sèrie Aspres (Palexeralf típic) constitueixen una excepció en la seva morfologia, ja que la seva naturalesa quarsítica ha permès desenvolupar sòls neutres o lleugerament àcids; en canvi, quan aquests sòls tenien carbonats en el seu material originari, han donat lloc a Palexeralfs petrocàlcics.

Els sòls de la sèrie Ventalló (Palexeralfs petrocàlcics de les terrasses Plistocenes del Fluvià) són sòls típicament policíclics, en què l'erosió i l'aportació de nous materials procedents dels relleus circumdants ha jugat un paper fonamental en el seu desenvolupament. Pel que fa a la sèrie Armentera (Xerofluvent típic), aquesta posa en evidència que, en superfícies joves de l'Holocè i en sòls cultivats, calcaris, d'una elevada capacitat de retenció d'aigua, difícilment s'hi desenvolupa un horitzó càmbic. Finalment, la sodificació acompanyada d'alcalinització (sòls de la variant Closes), és un procés molt ràpid quan es donen les circumstàncies (factors formadors) adients com és el cas de la dessecació de l'Estany de Sant Pere.

En el cas dels sòls profundament modificats, com és el cas dels bancals de les Garrigues (Boixadera *et al.*, en capítol 3) o els *camellones* dels Llanos de Moxos (Bolívia) (Boixadera *et al.*, en capítol 5), el model sòl – paisatge que cal aplicar a la cartografia presenta unes carències evidents ja que es consideren com a sòls "naturals", bàsicament perquè no estan previstos en el sistema taxonòmic emprat. Una possible solució es recollir-los en els diferents sistemes taxonòmics, en funció de les seves propietats morfomètriques intrínseques, i no com a la *World Reference Base* (IUSS, 2014) on estan recollits, en el cas dels bancals, només segons la seva morfologia externa (qualificador Escalic), que no deixa de ser equivalent a una fase.

6.1.3. Els sòls derivats de processos antropogènics i la seva classificació

En aquesta tesi s'ha investigat únicament aquells sòls que han estat profundament pertorbats, on el sòl originari no es pot reconèixer o roman enterrat (Bryant *et al.,* 1999). Malgrat això, la pràctica totalitat dels sòls té alguna empremta humana, conseqüència de les activitats antròpiques que s'hi ha desenvolupat (Buol *et al.*, 1980; Fanning *et al*., 1989; Bryant *et al*., 1999). En tots els casos que s'han investigats (bancals, *camellones* o sòls sòdics de l'Empordà), s'ha trobat un conjunt de característiques morfomètriques dels perfils que permeten plantejar la seva classificació en els esquemes d'alguna de les taxonomies ja existents.

Els models de classificació moderns i de més abast, com ara *Soil Taxonomy* (SSS, 1960, 1975, 2014) o la *World Reference Base for Soil Resources* (IUSS, 2014) s'utilitzen propietats morfomètriques del perfil per definir classes, amb un ús molt restringit de propietats relacionals (Evans *et al*., 1999). El que un sòl tingui un lloc adient dins d'un sistema taxonòmic permet la seva cartografia i el seu estudi, elements que fan avançar en el coneixement de la coberta edàfica, en la seva modelització (mapes de sòls) i en la millora de la planificació dels seus usos.

Pels casos estudiats en aquesta tesi en què el sòl apareix més dràsticament modificat, s'ha pogut definir un conjunt de caràcters morfomètrics amb un ús potencial per a la classificació. Així, pels sòls de *camellones* (Boixadera *et al*., en capítol 5), la variació a escala microtopogràfica (llom i canal del camelló) del pH, la saturació d'alumini, condicions de drenatge expressades en la morfologia redoximòrfica), l'absència de carbó i artefactes, els colors i el contingut de P similar als dels sòls naturals de l'entorn, a més de la presència, en tot el material remenat, de revestiments de llim i argila, poden servir per definir un tipus de sòl. En aquest context, poden ser d'ajut les propietats relacionals, com són la morfologia superficial, l'associació amb altres obres de terra (lloms, terraplens, dics, etc.) i la informació històrica.

Pel que fa als bancals antics de pedra seca, les característiques morfomètriques trobades tenen menys resolució cara a la classificació. La presència d'horitzons enterrats, que no sempre es dóna, la presencia de carbons, artefactes i continguts de P elevats i la morfologia superficial serien les principals propietats. S'hi podria afegir també l'existència d'estructura edàfica i la irregularitat en els límits entre horitzons. Aquesta podria ser una proposta per un conjunt dels bancals, i quedarien exclosos aquells on les condicions són molt diferents (per exemple els bancals on es conrea l'arròs del sud-est asiàtic en què el règim d'humitat és molt diferent). Aquesta proposta milloraria la situació actual en què el reconeixement a través del qualificador escàlic a la WRB implica una associació forçosa a una fase i sense cap implicació quant a la seva morfologia.

Finalment, cal fer esment dels sòls sòdics estudiats. En el cas del Calciustept sòdic descrit a l'Empordà (Boixadera *et al*., en capítol 3), la seva morfologia (il·luviació de llim i argila; col·lapse de l'estructura) no queda ben reflectida dins del subgrup Sòdic, ja que no es pot qualificar tampoc com a natric. Aquesta és una situació molt freqüent i que ha estat força estudiada (Walter, 1985; Rodríguez *et al.*, 1998). Cal indicar que aquí tampoc no es recull adequadament el procés antropogènic responsable.

Alguns sistemes taxonòmics, com *Soil Taxonomy*, tenen previst l'acomodar fàcilment certes pertorbacions molt comunes (com ara el llaurat fins a 18 cm que seria el cas paradigmàtic), mentre que d'altres modificacions s'hi poden encabir. Com que aquestes modificacions són cada cop més freqüents i a una escala major, és comprensible la necessitat de modificar aquests sistemes.

6.1.4. Els sòls com a registre paleoambiental

En aquest punt es vol destacar la significació dels sòls estudiats com a registre paleoambiental de l'entorn en què es troben. Els principals processos observats estan relacionats amb l'hidromorfisme, la il·luviació d'argila i la translocació de carbonats. Un aspecte molt significatiu és la velocitat amb què es desenvolupen aquests processos formadors. Les datacions obtingudes amb els loess fan palès que en períodes llargs de temps (17.000 anys) no es desenvolupen horitzons càlcics a la part oriental de la Depressió de l'Ebre. Si es contrasten aquestes xifres amb les de datacions de les terrasses del Baix Segre, es comprova que van en la mateixa direcció (Badia *et al*., 2009).

En el cas dels *camellones* dels Llanos de Moxos, la datació de l'humus del perfil M0X-51 permet afirmar que, com a mínim, el sòl més jove té 6000 anys, temps en què s'ha desenvolupat l'Alfisol i on després es va construir el *camelló*. El perfil M0X- 99/8 presenta una seqüència encara més complexa (un Inceptisol en la part superior i dos Alfisols subjacents), per la qual cosa indica un procés agradatiu continuat dels afluents del riu Madeira en aquella zona.

En el cas dels bancals de les Garrigues, convé destacar dos registres temporals molt interessants. En el primer, de curt termini i que s'estén, com a molt, fins a 1.500 anys A.C. (Boixadera *et al.,* 2016) es constata que en aquests sòls no hi ha un rentat significatiu de carbonats (no es desenvolupen acumulacions toves de carbonat càlcic en el sentit de *Soil Taxonomy* (SSS, 2014), malgrat que l'estructura granular es desenvolupa a tot el sòl nou. Pel que fa als sòls enterrats que apareixen als bancals estudiats, aquests ens permeten afirmar que, d'acord amb la datació de l'humus, el paisatge edàfic en un període a l'entorn de l'època romana estaria constituït per Mollisols.

Un altre aspecte que hom vol destacar d'aquest registre són els aspectes concrets de valor històric dels usos del sòl i la seva coevolució en el procés de la seva formació. Aquí, caldria destacar-ne dos, el dels *camellons* i el dels bancals. Els fitòlits trobats en els *camellons* de Moxos revelen que aquests sòls van ser utilitzats per al conreu de blat de moro, fet en què coincideixen altres autors. El registre pol·línic, en aquest cas dels fitòlits, ha aportat menys informació, però en el cas dels bancals de les Garrigues revela que van ser construïts per al conreu de l'olivera.

6.2. Conclusions

De la recerca realitzada se'n poden extreure les següents conclusions:

1. Les metodologies emprades en aquesta tesi, i que en molts casos partien de cartografies de sòls ja existents, han permès aprofundir en el coneixement del model sòl-paisatge de les diferents àrees on s'ha desenvolupat aquesta investigació i, per tant, en una millora significativa de les mateixes.

2. La identificació de determinats llims de la Vall de l'Ebre com a loess, i la seva conseqüent caracterització i datació, són una contribució significativa per entendre la coberta edàfica d'aquesta regió.

3. L'estudi dels bancals de les Garrigues i dels *camellones* dels Llanos de Moxos ha permès realitzar propostes per a la classificació d'aquests sòls antropogènics. Aquesta classificació es basa en els caràcters morfomètrics identificats com a distintius i permet una millor cartografia i maneig d'aquest sòl.

4. L'aprofundiment en la morfologia i gènesi dels sòls de referència estudiats a l'Empordà ha permès definir clarament les característiques dels sòls en les principals geoformes i, així, millorar la cartografia en àrees similars.

5. L'estudi dels pòl·lens i fitòlits continguts en els bancals i *camellones* ha permès establir que, les oliveres en els primers, i el blat de moro en els segons, hi van ser cultivats. Aquesta informació ens aporta claus importants sobre el per què de la seva construcció, especialment en el cas dels *camellones*.

6. La recerca que s'ha portat a terme permet oferir algunes dades sobre l'escala de temps necessari per al desenvolupament de determinats horitzons diagnòstic o caràcters de sòls: l'absència de càmbics a l'Empordà, càlcics a la part oriental de la Depressió de l'Ebre, o els argílics als *Llanos* de Moxos.

Referències

Àvila A, Alarcón M, Castillo S, Escudero M, García Orellana J, Masqué P, Querol X. 2007. Variation of soluble and insoluble calcium in red rains related to dust sources and transport patterns from North Africa to northeastern Spain. *Journal of Geophysical Research* **112**: 1-14.

Badía D, Martí C, Palacio E, Sancho C, Poch RM. 2009. Soil evolution over the Quaternary period in a semiarid climate (Segre river terraces, northeast Spain). *Catena* **77**(3): 165-174.

Boixadera J, Poch RM, Lowick SE, Balasch JC. 2015. Loess and soils in the eastern Ebro Basin. *Quaternary International* **376**: 114-133.

Boixadera J, Riera S, Vila S, Esteban I, Albert RM, Llop JM., Poch RM. 2016. Buried A horizons in old bench terraces in Les Garrigues (Catalonia). *Catena* **137**:635-650.

Boulaine J. 1980. Pédologie appliquée. Collection Sciences Agronomiques. Masson, Paris.

Brunnacker K. 1969. Affleurements de loess dans les régions nord-méditerranées. *Revue de Geographie Physique et de Geologie Dynamique* **2**: 325-334.

Bryant RB, Galbraith JG, Russell-Anelli J. 1999. Defining classes for antropogenic soils in Soil Taxonomy: Progress and future direction. *In:* Kimble JM, Ahrens RJ, Bryant RB, Proc. Meeting of classification, correlation and management of anthropogenic soils. Nevada and California. 1999. pp. 3-6.

Bryant RB, Galbraith JM. 2002. Incorporating anthropogenic processes in soil classification. Soil classification: A global desk reference. CRC Press. Boca Raton, FL. pp. 57-66.

Buol SW, Hole FD, McCracken RJ. 1980 (2nd ed.). Soil Genesis and classification. The Iowa State University Press. Ames. Iowa.

Coudé-Gaussen G, Olive P, Rognon P. 1983. Datation de dépôts loessiques et variations climatiques à la bordure nord du Sahara algéro-tunisien. *Revue de Géologie Dynamique et Géographie Physique* **24**: 61–73.

Desir G, Gutiérrez Elorza M, Gutiérrez Santolalla F, Marín C. 2011. Las formas y depósitos eólicos de la Depresión del Ebro. pp. 563-581. *In:* Sanjaume Saumell E, Gracia Prieto FJ. (Eds.). Las dunas en España. Sociedad Española de Geomorfología. Cádiz.

Fanning DS, Fanning MCB. 1989. Soil. Morphology, genesis and classification. John Wiley and Sons, New York.

Herrero J, Porta J, Fédoroff N. 1992. Hypergypsic soil micromorphology and landscape relationships in Northeastern Spain. *Soil Science Society of American Journal* **56**: 1188-1194.

Hudson BD. 1992. The soil survey as paradigm-based science. *Soil Science Society of America Journal* **56**(3): 836-841.

IGC – DAR - ICC. 2010. Mapa geològic de Catalunya. Geotreball IV. Mapa de sòls. Térmens, full 359-2-2 (64-28), 1:25.000.

IGC – DAAM - ICC. 2011. Mapa geològic de Catalunya. Geotreball IV. Mapa de sòls. Les Borges Blanques, full 389-1-2 (65–30), 1:25 000. ICGC. Barcelona.

IUSS Working Group WRB. 2006. World Reference Base for Soil Resources 2006 (2nd ed.). *In:* World Soil Resources Reports No. 103 FAO, Rome.

Jenny H. 1941. Factors of soil formation: a system of quantitative pedology. McGraw-Hill. New York.

Mücher H, Sevink J, Bergkamp G, Jongmans J. 1990. A pedological and micromorphological study on Mediterranean loessial deposits near Gerona, NE-Spain. *Quaternary International* **5**: 9-22.

Muhs DR, Budahn J, Avila A, Skipp G, Freeman J, Patterson D. 2010. The role of African dust in the formation of Quaternary soils on Mallorca, Spain and implications for the genesis of Red Mediterranean soils. *Quaternary Science Reviews* **29**: 2518-2543.

Phillips JD. 2004. Geogenesis, pedogenesis, and multiple causality in the formation of texture-contrast soils. *Catena* **58**: 275–295.

Poch RM. 1992. Fabric and physical properties of soils with gypsic and hypergypsic horizons o fthe Ebro valley. PhD thesis. Universiteit Gent. Ghent. Belgium.

Riba O, Llamas MR. 1962. Los terrenos yesíferos Triásicos y Terciarios de las proximidades de Estada (Huesca). *I Coloquio Internacional sobre Obras Públicas en los terrenos yesíferos.* T.V. Communications. Tema 6. Servicio Geológico de Obras Públicas, 107-121.

Rodríguez-Ochoa R, Usón A, Olarieta JR, Herrero J, Porta J. 1998. Irrigation from the Sixties: Flumen-Monegros. Chapter 3.3. pp.1-51. *In:* Boixadera J, Poch RM, Herrero C. 1998. Tour Guide B8:

Smith GD. 1965. Lectures on soil classification. Pedologie 4, special issue. Belgian Soil Science Society. Ghent. Belgium.

Soil information for sustainable development. Guidebook for field trip B8 (Catalonia and Aragon, Spain). 27 August-2 September 1998. 16^{th} World Congress of Soil Science. International Union of Soil Sciences. Lleida.

Solé Sabaris L, Porta J, Solé N, Cuerda J, Muntaner A, Colom G. 1957. Livret guide de l'excursion L: Levant et Majorque, 5ème Congrès International INQUA. Madrid-Barcelona.

SSS - Soil Survey Staff, Soil Conservation Service, United States Department of Agriculture. 1960. Soil classification. A comprehensive system. 7^{th} approximation. Washington, DC.

SSS - Soil Survey Staff, Soil Conservation Service, United States Department of Agriculture. 1978. Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. Agriculture Handbook 436. Washington, DC.

SSS - Soil Survey Staff. 2014. Keys to Soil Taxonomy (12th ed.) USDA-NRCS. Washington, DC.

Walter Ch. 1985. Caractérisation de sols à horizon natrique. Mémoire de DEA. Institut National Agronomique Paris-Grignon. Paris.

Yaalon DH. 1987. Saharan dust and desert loess: effect on surrounding soils. *Journal of African Earth Sciences* **6**: 569-751.

Yaalon DH, Ganor E. 1973. The influence of dust on soils during the Quaternary. *Soil Science*: **116**(3):146-155.